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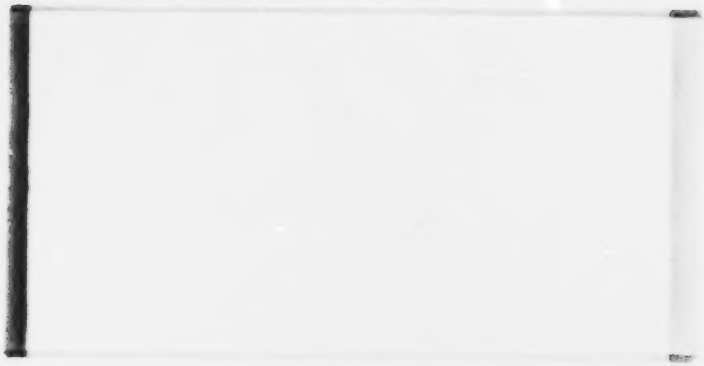

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RAPID INDUCTION HEATING FOR SEPARATION OF ROLLED JOINTS PHASE I

Report No 85-270-K

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ABSTRACT

A rapid induction heating technique was developed and applied in the Fuel Channel Replacement Program at Pickering NGS. This report describes the basic technological development of the process for the separation of pressure tube-end fittings-rolled joints without damaging the old end fittings. Other aspects of the development are high-lighted but these will be covered in more detail by subsequent reports.

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EXECUTIVE SUMMARY

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Stations & Underground Section
Electrical Research Department

In 1974 and 1975 leakages of heavy water were experienced due to small cracks in some of the pressure tubes at Ontario Hydro's Pickering Nuclear Generating Station. In view of the need to repair these leaks and the possibility of retubing a complete reactor, it was proposed to develop an advanced technique for tube replacement. To reduce the cost of replacing the tubes, the end fittings were to be retained on one side of the calandria. This generated the requirement to disassemble the pressure tube-end fitting-rolled joints (P/T-E/F-R/J) without damaging the old end fittings. In 1975 Ontario Hydro Research (OHR) proposed and studied initially two electromagnetic techniques for achieving clean separation of rolled joints. The first technique was based on an induction heating and mechanical pulling procedure. This technique had limited success and was later dropped due to problems with necking and breaking of pressure tubes. A more elegant technique called magnetic implosion was proposed and demonstrated on scaled down models by OHR. Theoretical and experimental studies established the feasibility of a concept of imploding (collapsing from inside) the tube at the joint by means of a special magnetic impulse force. With financial support from Nuclear Systems Department, further development of special equipment for this technique continued but the technique was dropped due to the need for a small gap at the P/T-E/F interface and equipment delivery problems. OHR proposed an alternative induction heating technique (rapid heating and cooling) to create the needed gap

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by shrinking the pressure tube at the rolled joint area. This alternative concept was then adopted as a base line technique for P/T-E/F-R/J separation during the planned LSFCRP of Pickering 'A' NGS and is the subject of this report.

The LSFCRP program was slowed down by 1982 by the REFAB decision, but development of the rapid induction heating technique was again reconsidered after the P2G16 pressure tube rupture. At the request of Pickering Engineering Department, the development program started in January 1984 and was further accelerated following a decision by the Ontario Hydro Board of Directors to proceed immediately with the preparation for early retubing of Units 1 and 2 at Pickering 'A' NGS. Rapid induction heating technique was selected for the separation of the P/T-E/F-R/J. There are several advantages of this technique over the other alternative techniques (eg. cutting and milling). These include (saving one end fitting from each tube), reduction of man-rem exposure, and reduction of the amount of radioactive debris which may result from cutting.

The developmental program carried out at OH Research to implement the rapid induction heating technique for retubing of Pickering NGS was divided into the following four phases:

Phase I	R/J qualification program at OH Research.
Phase II	Separation of irradiated R/J at CRNL.
Phase III	Integration of electrical and mechanical equipment at Canadian General Electric (CGE).
Phase IV	Implementation at Pickering 'A' NGS.

Due to the on-going activities and time limitation, this report describes only the work performed in Phase I of the program. It covers the period from January 13, 1984 to June 2, 1984. Reports on the other phases will be prepared and issued in the near future. To give a more complete picture of the project, major accomplishments of each phase are listed below.

Phase I R/J Qualification Program At OH Research

A reliable process for P/T-E/F rolled joint separation using a rapid induction heating technique was developed. A total of 26 rolled joint specimens were separated and forwarded to CGE for refurbishing and analysis. A prototype transmission line and coil assembly was built and supplied to CGE for integration into the final system for field use. The 160 kW induction heating system which was used for developmental work was shipped to Chalk River Nuclear Laboratory (CRNL) for further testing with irradiated rolled joint specimens.

Phase II Separation Of Irradiated R/J At CRNL

Problems associated with water being trapped inside the rolled joints were encountered when tests were carried out with the radioactive specimens. A warm-up procedure was designed and incorporated into the induction heating procedure that had been established in Phase I. The rapid induction heating technique was proven capable of separating the irradiated P/T-E/F rolled joint specimens.

Phase III Integration Of Electrical And Mechanical Equipment At CGE

Two 250 kW induction heating systems were commissioned at CGE Peterborough by OHR staff. Various induction heating parameters determined for the original 160 kW induction heating system were translated to be used by the 250 kW systems. The systems were shipped to Pickering NGS for field use. A new induction heating coil (seven turns instead of six turns) was also introduced which was designed to reduce the sensitivity of axial coil positioning.

Phase IV Implementation At Pickering 'A' NGS

This phase included the training of site staff, preparation of various reports and procedures, assisting in installation and commissioning of the two 250 kW induction heating systems in Pickering Units 1 and 2, general consulting, and trouble shooting. In addition to the above, a number of experiments were conducted in the Electromagnetic Laboratory to support the Pickering Engineering Department in solving various practical field problems as they were encountered.

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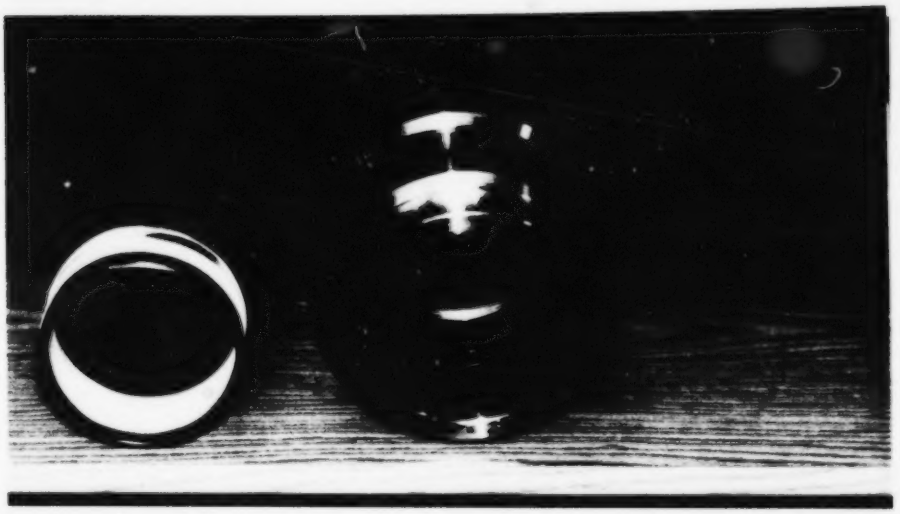
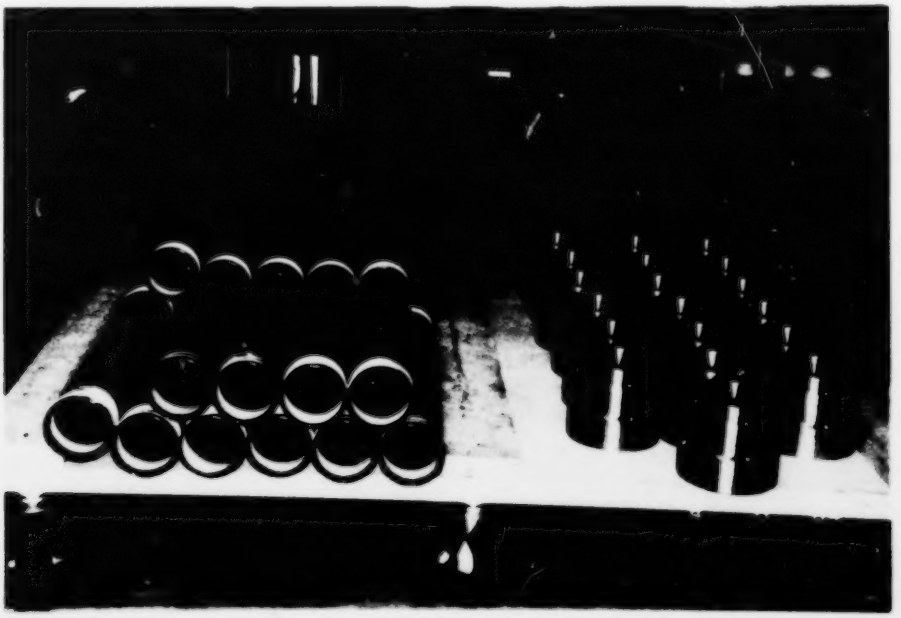
RAPID INDUCTION HEATING FOR SEPARATION OF ROLLED JOINTS
PHASE I





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To Mr. H.C. Mahon
Acting Manager
Pickering Engineering
Design & Development - Generation

RAPID INDUCTION HEATING FOR
SEPARATION OF ROLLED JOINTS
PHASE I

1. BACKGROUND AND INTRODUCTION

In 1974 and 1975 leakages of heavy water were experienced due to small cracks in some of the pressure tubes at Ontario Hydro's Pickering Nuclear Generating Station. In view of the need to repair these leaks and the possibility of retubing a complete reactor, it was proposed to develop an advanced technique for tube replacement. To reduce the cost of replacing the tubes, the end fittings were to be retained in place at one side of the calandria. This generated the requirement to dissassemble pressure tube-end fitting-rolled joints (P/T-E/F-R/J) without damaging the old end fittings. In 1975 Ontario Hydro Research proposed and studied initially two electromagnetic techniques for achieving clean separation of rolled joints. The first technique was based on an induction heating and mechanical pulling procedure. This technique had limited success and was dropped when end fitting supply was assured. A more elegant technique called magnetic implosion was proposed and demonstrated on scaled down models by OHR. Although the theoretical and experimental studies established the feasibility of a concept of imploding (collapsing from inside) the tube at the joint by means of a special magnetic impulse force, the technique was dropped due to equipment delivery problems and need for a small gap at the P/T-E/F interface. Ontario Hydro Research proposed an alternative induction heating technique (rapid heating and cooling) to create the needed gap by shrinking the pressure tube at the rolled joint area. This alternative concept was later adopted as a base line technique for P/T-E/F-R/J separation and is the subject of this report.

In March 1984, a decision was made by the Ontario Hydro Board of Directors to proceed immediately with preparations for retubing of Units 1 and 2 at Pickering 'A' NGS. The rapid induction heating technique was selected for the separation of the P/T-E/F-R/J. The application of this technique is attractive for the following reasons:

a) It is a clean method which by comparison with other methods like cutting will not produce significant amounts of radioactive debris, requiring collection and control.

b) It lends itself easily to automation. This reduces the man-rem exposure.

c) The end fittings would not be damaged and hence would be available for reuse at a substantial saving to the company.

A program was carried out at OHR to implement the rapid induction heating technique for retubing of Pickering NGS. This program was divided into the following four phases:

Phase I R/J qualification program at OH Research.
Phase II Separation of irradiated R/J at CRNL.
Phase III Integration of electrical and mechanical equipment at CGE.
Phase IV Implementation at Pickering 'A' NGS.

2. HIGHLIGHT OF EACH PHASE

This report describes only the work performed in Phase I of the program covering the period from January 13, 1984 to June 2, 1984. Reports on the other phases will be prepared and issued in the near future. To give the reader a more complete picture of the project, major accomplishments of each phase are listed below.

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This phase included the training of site staff, preparation of various reports and procedures, assisting in installation and commissioning of the two 250 kW induction heating systems in Pickering Units 1 and 2, general consulting, and trouble shooting. In addition to the above, a number of experiments were conducted in the Electromagnetic Laboratory to support the Pickering Engineering Department in solving various practical field problems as they were encountered.

3. OBJECTIVES (Phase I)

Work in Phase I was financed by Pickering Engineering Department. The work performed by OHR included the following:

a) Development of the P/T-E/F rolled joint (R/J) separation process.

b) Design, build and test some of the special equipment required for this application in the form of prototypes suitable for field use.

c) Provide a technical specification for the induction heating equipment suitable for field use, to be procured from external suppliers.

d) Development of the software for process control and specification of the instrumentation required for this application.

e) Integration of the various pieces of equipment into a system and qualification of the process. The qualification criteria as agreed with Pickering Engineering was the successful separation of 14 samples of P/T-R/J.

A total number of 26 P/T-R/J samples were separated but the first 12 were used to establish the parameters of the process.

4. WORKPIECE DESCRIPTION

The 26 P/T-R/J samples used in this program were representative of those used in Pickering 'A' Units 1 and 2. The P/T is in this case made of the alloy Zircaloy-2 (Zr-2) and has a wall thickness of 5.23 mm.* Each sample had a total length of approximately 26 1/2" and incorporated a short piece of end fitting of about 6 1/2".

Due to the limited number of Zr-2 rolled joints available, Ontario Hydro Research performed the initial tests to define parameters of the process, using six P/T-R/J samples representative of Pickering Units 3 and 4 which had a thinner P/T wall (4.16 mm) and were made of Zirconium-Niobium 2.5% by weight. These samples also included a short piece of end fitting.

5. DESCRIPTION OF THE RAPID INDUCTION HEATING PROCESS

A coil designated as load coil is centered inside the P/T-R/J. This coil is supplied with radio frequency power in the order of 2000 A, 3000 V RMS at 125 kHz for a number of seconds. The small clearance between the load coil and the work piece allows for good electromagnetic coupling which creates induced currents in the work piece in response to the rapidly time varying field. The linkage of the field generated by the load coil and the work piece is not uniform across the wall of the P/T, this is due to a phenomenon known as skin effect whereby the magnetic field can penetrate a metal only up to a certain depth depending on the frequency of the field, permeability μ, and conductivity σ, of the material according to the equation:

$$\delta = \sqrt{\frac{2}{\omega\mu\sigma}} \qquad \text{where } \omega = 2\pi f$$

By choosing a sufficiently high frequency f, the penetration depth δ will be less than the P/T wall thickness, this will confine the circulation of induced currents to the shallow layer adjacent to the P/T inner wall. The P/T outer wall will then attain a lower temperature thus protecting the E/F from overheating. Power is applied for a short duration to limit the heat transfer through the P/T wall to the E/F. After power is turned off, the work piece is subjected to a fast cool-down, by blowing air on it. As a result, the P/T shrinks over the shock heated portion. In general, a number of heating cycles followed by cooling cycles as described above are required to produce enough shrinkage to make the P/T-R/J loose enough to be

*Note, both SI and Imperial Units were used to make use of the available gauges and to facilitate the needs of the client and contractor organization.

separated. The number of heating cycles may be minimized by increasing the applied power level while keeping the heating cycle to a short duration to limit the P/T peak temperature below melting point and the E/F temperature to an acceptable limit.

Ideally the amount of shrinkage required should be equal to twice the depth of the E/F groove that indents with the P/T. A minimum theoretical shrinkage of 0.076" is thus required everywhere along the rolled joint portion of the P/T. However, due to variation in concentricity in positioning the load coil and other factors such as the asymmetry produced by the half turns at the front and back of the coil the shrinkage is not uniform, either for different axial or angular locations. In practice shrinkages in the order of 0.120" are required on average.

6. EQUIPMENT USED AND TEST SETUP

The following pieces of equipment were required to carry out the laboratory work to develop the shock heating process for LSFCR.

a) 160 kW Induction Heating Generator, Lepel model T160-3-KC9-TL2

b) Load Coil Transformer (LCT)

c) Transmission Line (OHR Dwg No 5364)

d) Load Coil (OHR Dwg No 200219)

e) Transmission Line Support Stand (OHR Dwg No 5346)

f) 400 kVA Input Transformer

g) Oscillator Tube Section (OTS) Cooling System including: 200 L holding tank and hoses plus 3/4 hp motor pump set to be supplied with 208 V, 3-phase.

h) Computer HP85

i) Programmable power supply HP 59501A

j) Data Acquisition System HP 3497A

k) Capacitive Voltage Divider

l) Current Transformer

m) Clarke Hess RF meter model 255

n) Hydraulic Table

o) Pulling Apparatus

The various pieces of equipment are configured as shown in the block diagram in Figure 1. The actual arrangement is shown in Ontario Hydro Research drawing No 40324. The 400 kVA transformer (item f) is provided to match the line voltage (600 V) to the rated ac input voltage (460 V) of the Lepel equipment.

The 160 kW Induction Heating Generator, item (a), consists of a dc power supply and an Oscillator Tube Section (OTS). A simplified electrical schematic of this equipment is shown in Figure 2.

The dc power supply is essentially a 3-phase diode bridge supplied with ac power from the rectifier transformer. There is a saturable reactor on each line of the primary of the rectifier transformer. The saturable reactors and the rectifier transformer are both internal to the dc power supply.

The saturable reactors are used as a variable series impedance in the lines connected to the rectifier transformer. The value of this impedance is controlled by the dc current through the control coil. The magnitude of the ac input voltage to the bridge is thus controlled and as a result the magnitude of the dc output voltage from the bridge; a range of adjustment from approximately 1 kV dc to 15 kV dc is possible. The dc power supply is water cooled; it takes tap water through a 1-1/2" inlet line and it discharges the cooling water to drain through an outlet line which is also 1-1/2" in size.

The output voltage from the dc Power Supply is used to supply the OTS. The OTS is essentially a modified Hartley oscillator designed for Class C operation. The basic components are a multi tap tank inductor, an 8 x 0.0076 μF tank capacitor bank and a triode oscillator tube (ITT7560), all these components are water cooled. The power level coming out of the oscillator can be adjusted through the dc input voltage into the OTS. The frequency can be adjusted by proper selection of the tap on the tank coil. The oscillator tube grid must be properly biased for proper Class C operation. Adjustment of the grid setting or tuning of the OTS is done according to the chart in Figure 3 as per manufacturer's instruction. Tuning has to be done with the transmission line, load coil transformer and load coil connected and also with the work piece in the intended position. The tuning is accomplished by varying the position of a small coil which is magnetically coupled and concentric with the tank coil inside the OTS cabinet, the voltage induced in this coil is used as a feed back signal for the oscillator tube grid. A servo motor is provided for remote grid adjustment. Various interlocks exist to provide safety; for details the T160-KC9-TL2 Lepel operating and maintenance manual should be consulted.

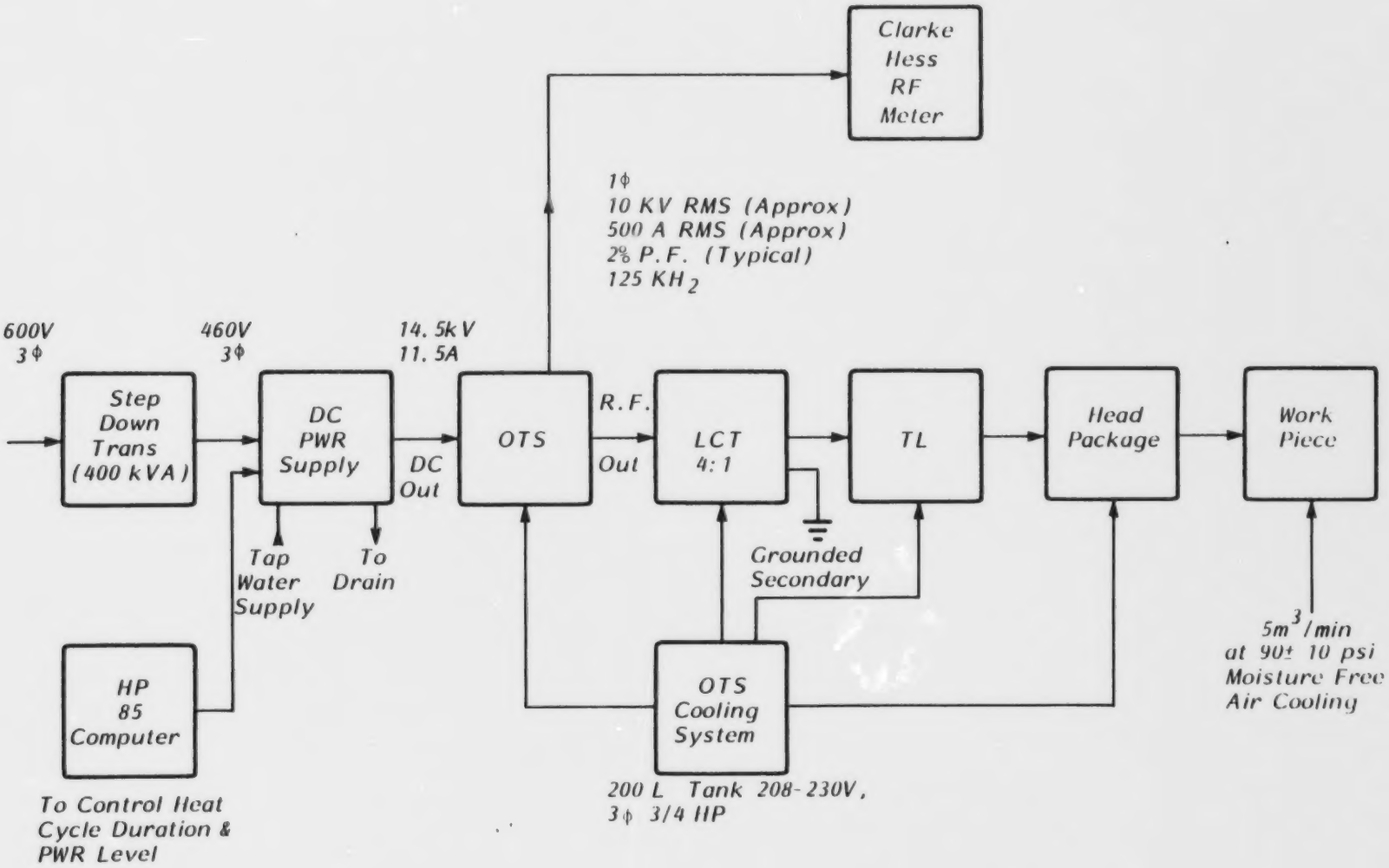

FIGURE 1

INDUCTION HEATING SYSTEM BLOCK DIAGRAM

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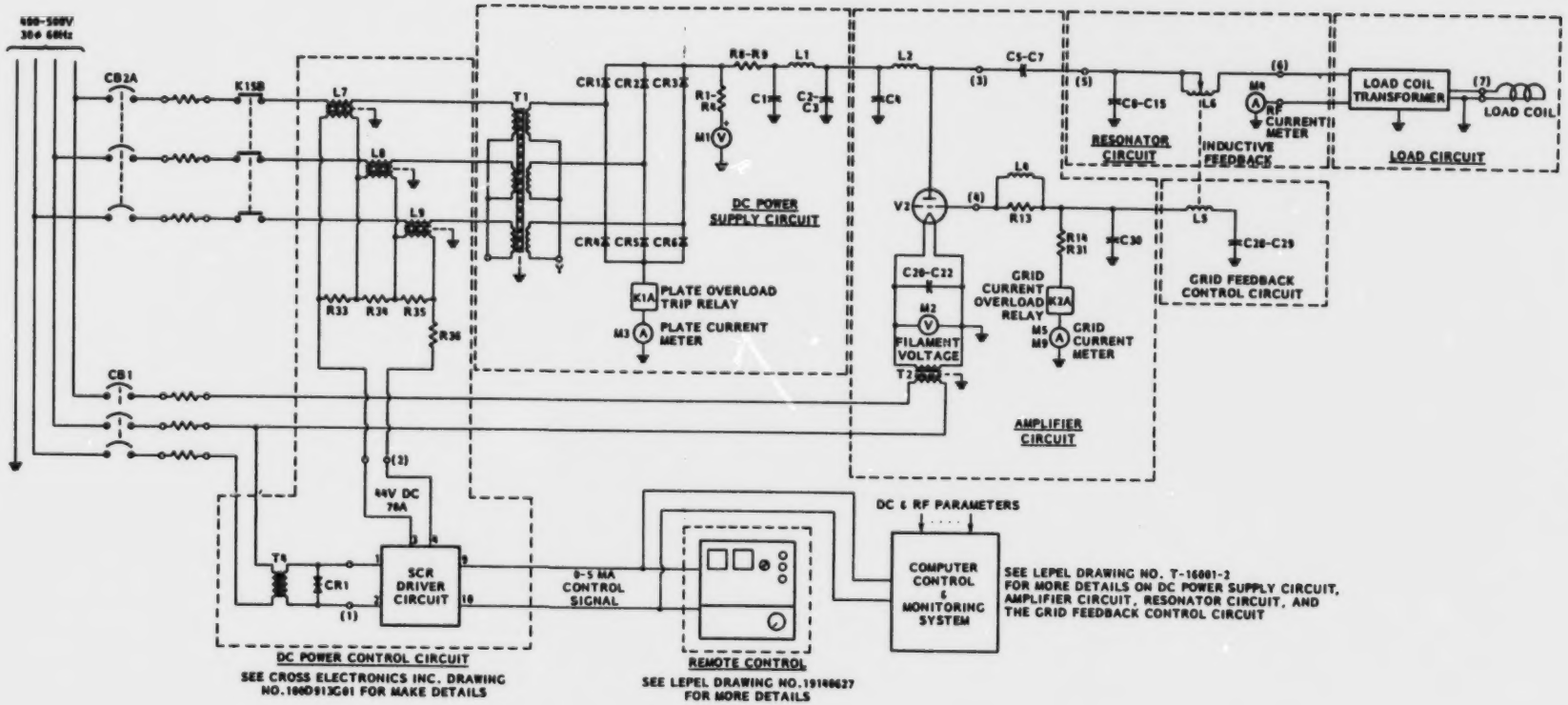

FIGURE 3
160 kW INDUCTION HEATING GENERATOR SIMPLIFIED SCHEMATIC

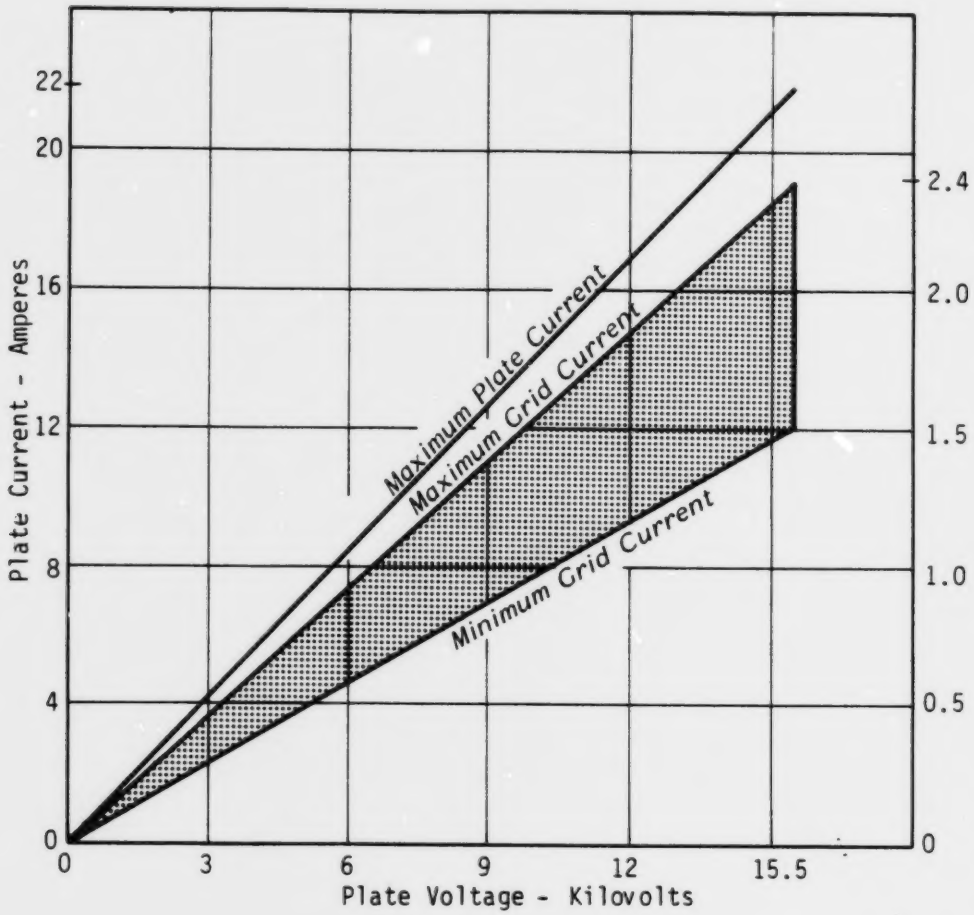

FIGURE 3

RECOMMENDED GRID AND PLATE CURRENT RANGES VERSUS PLATE VOLTAGE

The Load Coil Transformer (item b) is an air core transformer with both the primary and the secondary water cooled. The transformer ratio is 4:1 with the high-voltage side connected to the OTS and the low-voltage side connected to the Transmission Line. One terminal of the secondary must be grounded.

The Transmission Line is composed of two 144" long copper conductors made of 0.5 "x 1" x 0.062" (wall) tubing enclosed in a cylindrical aluminum shield of approximately 3.75" OD. The copper conductors are water cooled. The aluminum shield also encloses air lines to supply cooling air to the work piece. The air supply must be 90 ± 10 psi and the air must be dry. For this purpose a moisture trap was installed at the supply valve.

The air flow through the work piece is about 5 m^3/min (174 ft^3/min). The cooling water through the transmission line and coil is 3.0 gpm (US) at 24 psi (g) at the inlet and pressure drop of 12 psi(g). The cooling water temperature at the OTS inlet must be kept below 27°C. Tap water was used, although the use of demineralized water is recommendable.

The Load Coil is a six turn, 3.5" OD cylindrical coil made of 0.25" x 0.5" x 0.048" (wall) rectangular copper tubing that takes power and cooling water from the transmission line. A quartz glass sleeve of dimensions 89 mm ID x 95 mm OD x 4.75" long adds dielectric strength between the coil and the work piece to prevent flashover.

The HP85 computer was used to control and monitor the heating process. There are two basic inputs to be entered by the operator: Power level and heat cycle duration. There may be other inputs to be entered by the operator during development testing such as P/T temperature limit and E/F temperature limit. The actual P/T and E/F temperatures are analog inputs measured by thermocouples. The computer controls the induction heating cycle (both power level and duration) by regulating the level of the dc current input to the SCR driver circuit. This SCR circuit, in turn, controls the voltage output of the saturable reactors. The control scheme is open loop control, and control signals are provided by the computer and supplied to the SCR driver by the programmable power supply, item (i).

Various dc and RF parameters were monitored by the computer during, and for a short period after, the heating cycle. Dc parameters (voltages, current and temperature) are sampled by the Data Acquisition unit or Data Logger, item (j). RF parameters (voltage, current and power) are sampled by the Clarke Hess RF meter (item m) in conjunction with the capacitive voltage divider and the current transformer (items k and l). All communication among devices (computer, programmable power

supply and data acquisition unit etc) is accomplished via the HP-IB buses. For more information on the control and monitoring system, please refer to Reference 1.

The OTS cooling system item (g), provides cooling for the OTS, LCT, Transmission Line and Load Coil. A simplified Flow Diagram is shown in Figure 4. A total flow of 60 gpm (US) at 40 to 65 psi(g) at the OTS inlet is specified by the manufacturer for continuous operation at full load. For this particular application a flow of approximately 50 gpm (US) at 30 psi(g) at the OT inlet, was used.

The hydraulic table item (n) was used to support the work piece and to allow position adjustment for alignment of the work piece with respect to the load coil.

The pulling apparatus, item (o) consists of a hydraulic ram plus universal joint to provide straight pull and fixtures to bear against the E/F. The ram is attached to the P/T through a U-joint and bolted to holes on the P/T wall. The setup includes a pressure gauge. The calibration chart to convert pressure into force is shown in Figure 5. This pulling device was designed purely for the development phase and is not suitable for reactor work.

7. DESIGN AND SCHEDULING OF EXPERIMENTS

Due to the urgency of the situation at Pickering 'A' NGS, Ontario Hydro Research and Pickering Engineering Department (PED) were under pressure to shorten the duration of the shock heating developmental program, and to implement the technology in the field as soon as possible. As a result, the experiments were performed with a limited amount of time, specimens (number, type and geometry), and equipment. Furthermore, the scope of work was continually changing throughout the program to reflect changing requirements which made it difficult to design and schedule the various experiments. In spite of the above constraints, the required experimental results were obtained, and the shock heating process developed and qualified on time. Results are summarized in the next section. A system and a process for P/T-E/F rolled joint separation were developed and implemented. The system and process were made as simple as possible as requested by PED, so as to make them operational in the time available but not necessarily optimal. More work is required to optimize the system and process.

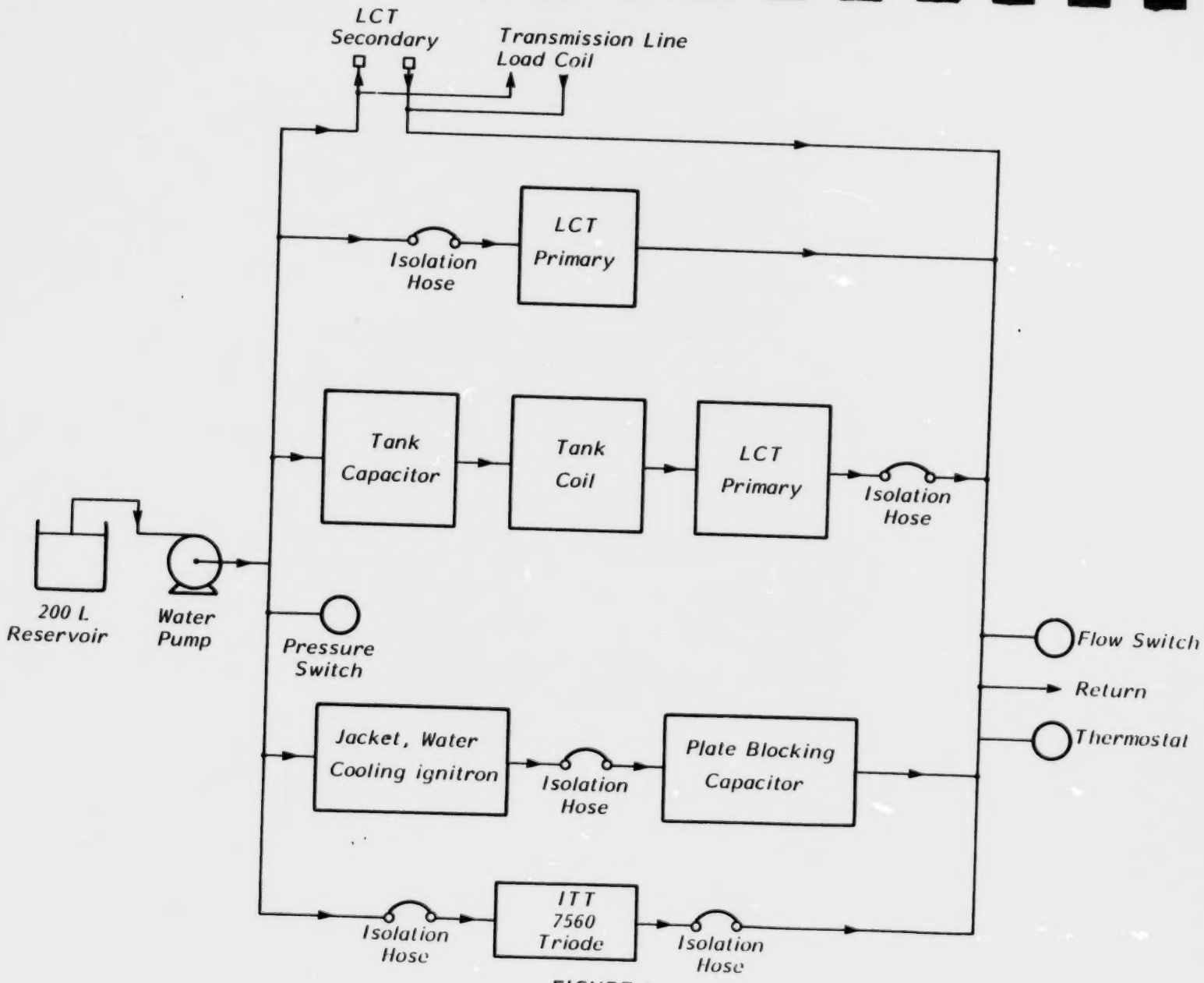

FIGURE 4
OTS COOLING SYSTEM SIMPLIFIED FLOW DIAGRAM

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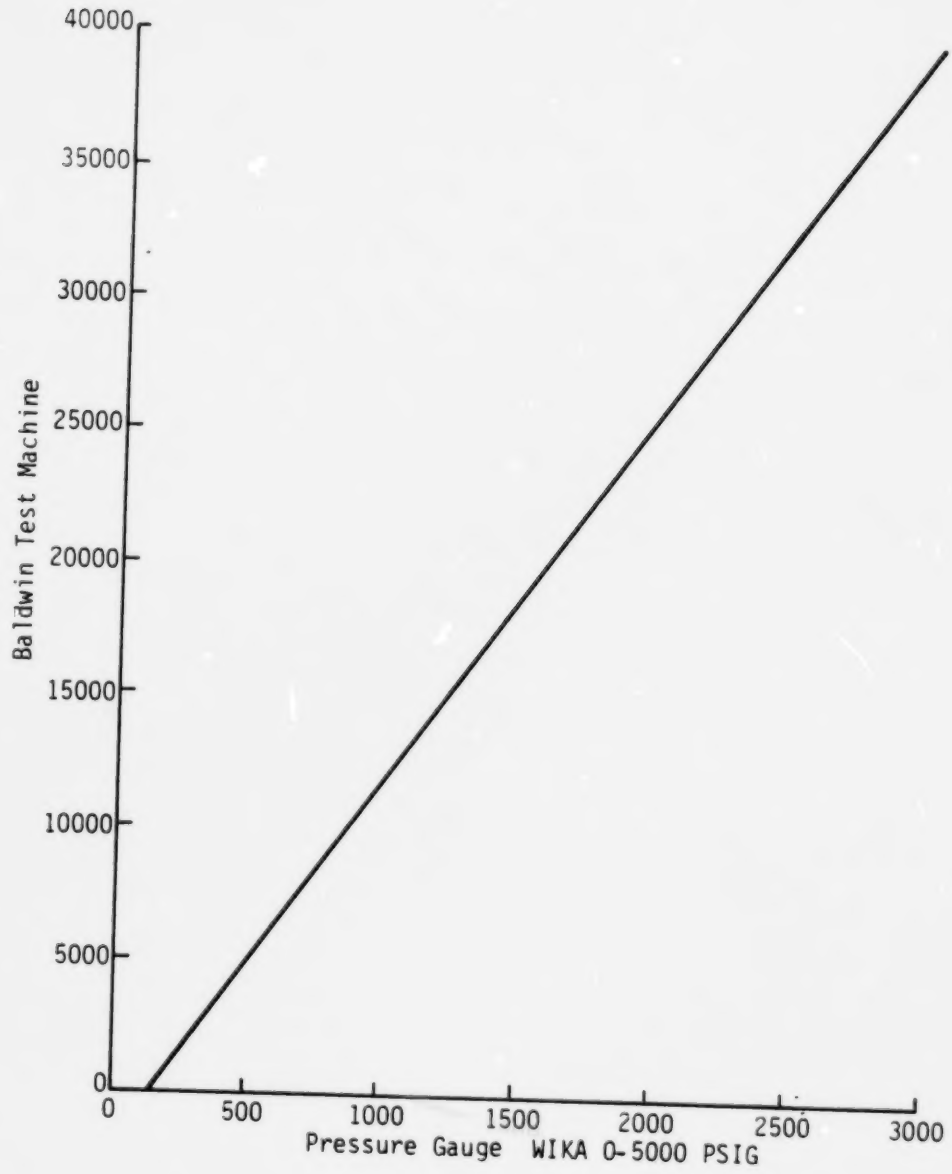


FIGURE 5
PULLING APPARATUS CALIBRATION CHART

8. EXPERIMENTAL RESULTS

A series of experiments were designed and completed for the P/T rolled joint separation program. These experiments involved six Zr-Nb 2.5% and 26 Zr-2 P/T specimens and were performed under the following constraints:

a) P/T temperature limit = 1400°C (not to be exceeded)
b) E/F temperature limit = 570°C (not to be exceeded)
c) Maximum Pulling Force = 3500 lbs

The following sections describe the objectives of each experiment and summarize the results obtained.

8.1 Selection of Induction Heating Coil

Four induction heating coil prototypes were designed and built for the experiments. These coils had different diameters and numbers of turns as shown below:

Coil #	Outer Diameter (inch)	# of Turns
1	3 3/8"	6
2	3 3/8"	8
3	3.5"	6
4	3.5"	8

Temperature profiles obtained from a sample piece of Zr-2 pressure tube using the above coils are shown in Figure 6. On the basis of the temperature profiles and equipment limitations coil #3 was selected since it produced the most uniform distribution of temperature over the three rolled joint groove locations.

8.2 Establishment of Induction Heating System Parameters

In order to achieve the separation of a P/T from the end fitting, various system parameters had to be determined. These parameters are listed below, together with the values obtained from results of various experiments. Parameters number 1 to 4 are machine parameters needed for the operation of the induction heating system. The remaining two are process parameters.

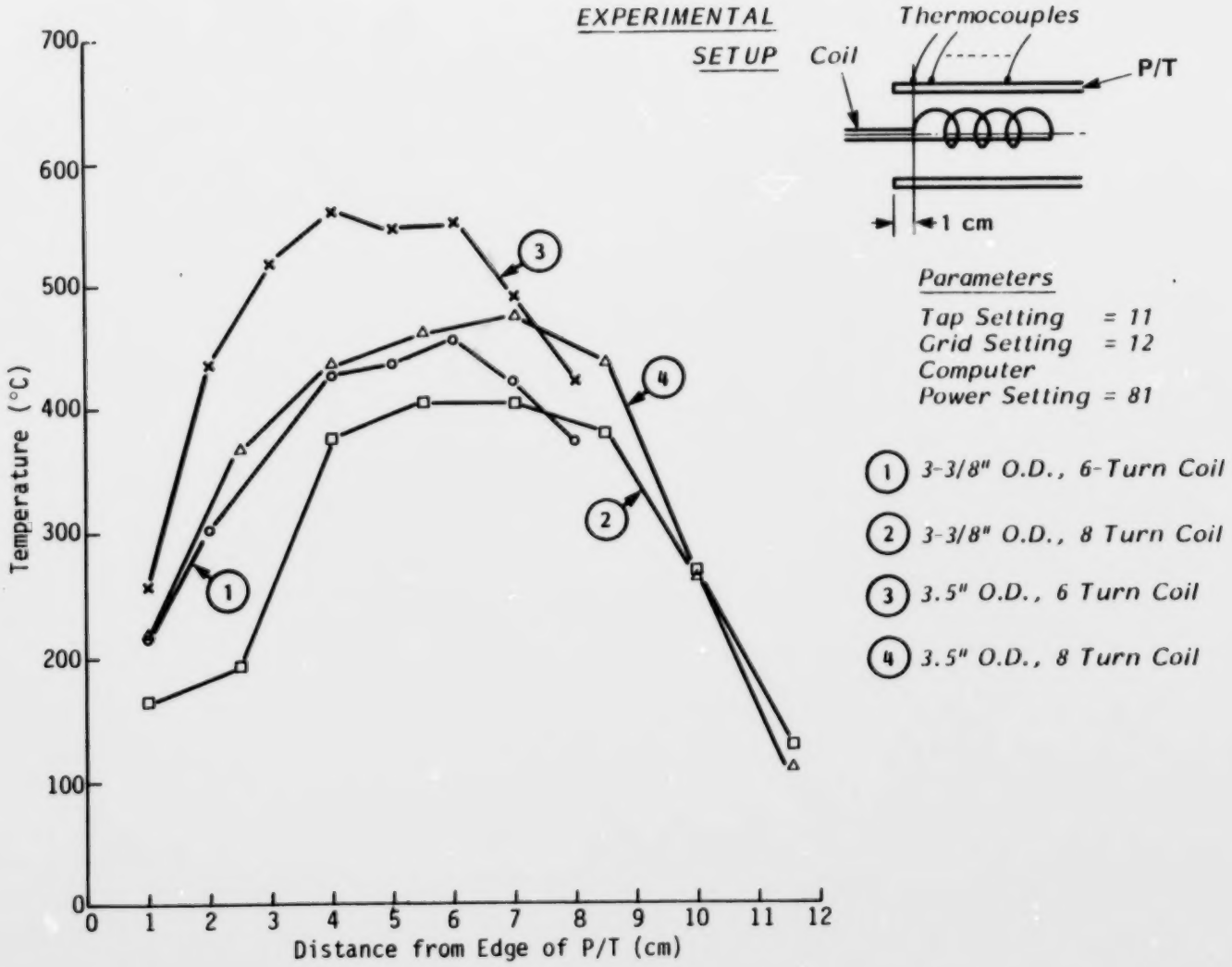


FIGURE 6

TEMPERATURE VERSUS DISTANCE PROFILE FOR VARIOUS INDUCTION HEATING COILS OBTAINED AT 13.5 SEC

#	Parameter	Value
1	Tap Setting	11
2	Grid Setting	74
3	Computer Power Setting	131
4	Dc Plate Voltage	13.6 kVdc
5	Heating Duration	30 s
6	Cooling Duration	30 min

These parameters were determined from experiments performed on six Zr-Nb-2.5% by weight, rolled joint samples with a six-turn coil. These samples were used because they were available and could be drilled for thermocouple installation. Also, the experiments were based on the assumption that Zr-Nb-2.5% samples were similar in material properties to Zr-2 samples. All parameters were selected based on the criterion that shrinkage of P/T could be achieved with some safety margin for both the shock heating equipment and the process.

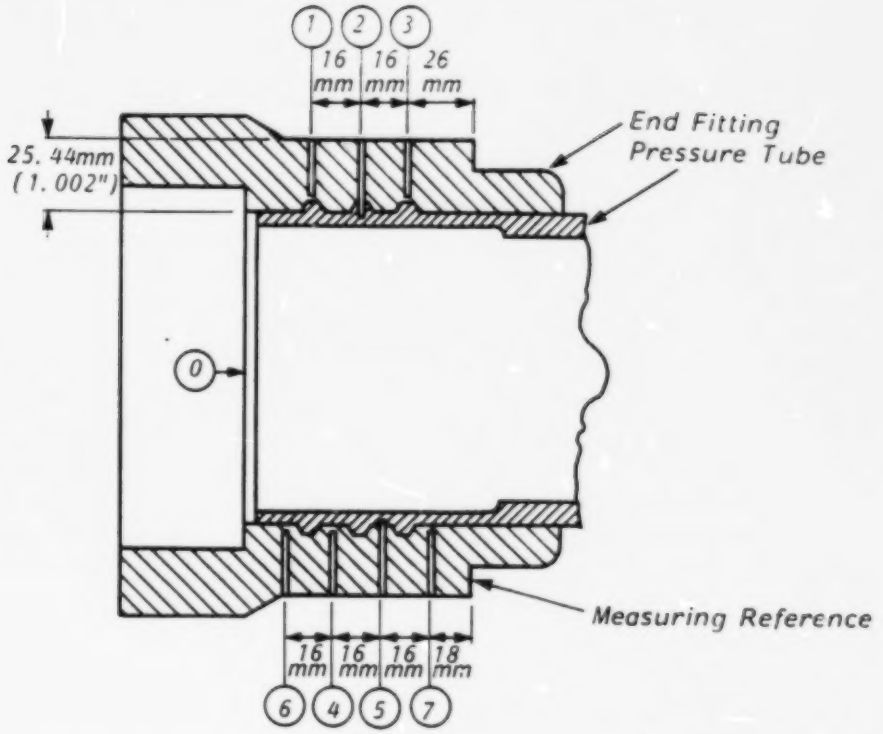
Temperature profiles as functions of time for a typical heating cycle obtained from a Zr-Nb-2.5% sample are shown in Figure 7. It should be noted that these temperature profiles correspond to one of the samples used in the early stages of the development program, before the values of the heat cycle parameters, as shown above, were established.

8.3 Selection of Coil Position

As described before, the induction heating coil is placed inside the P/T-E/F rolled joint. In order to concentrate the heat energy in the designated area, the coil position had to be determined. An experiment employing four Zr-2 P/T-E/F rolled joints was designed and completed to determine the coil position.The position of the coil (x) is as referenced in Figure 8. Shrinkage measurements at various positions of the rolled joint area after the first and second heating cycle with parameters as outlined in Section 8.2 were obtained for different coil positions. The results are summarized in Figures 9 and 10 which show the total average shrinkage as a function of position after the first and second cycle respectively. From Figure 10 it was concluded that the coil position, x = 5/16", was the best since it produced the most even shrinkage over the three rolled joint grooves.

8.4 Selection of Number of Heating Cycle

Tests were performed using eight Zr-2 samples. These samples could not be drilled for thermocouple placement as instructed by Pickering Engineering Department. The purpose of these tests



Thermocouples 1, 3, 6, 7 - 23 mm Deep (0.904")
2, 5 - To Centre of PT Wall
4 - 24.6 mm Deep (0.970")

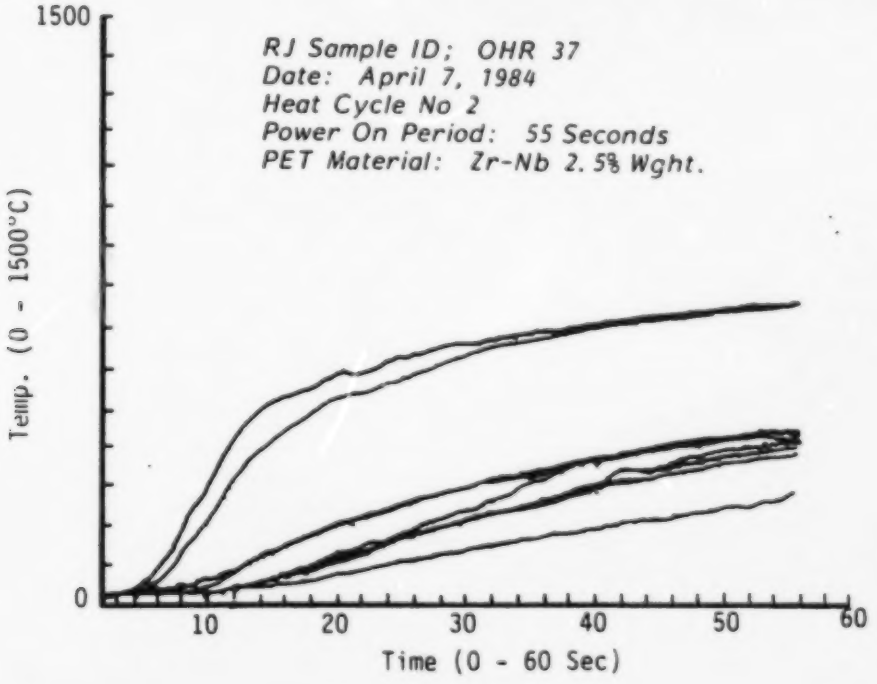


FIGURE 7
THERMOCOUPLE LOCATIONS AND TEMPERATURE PROFILE

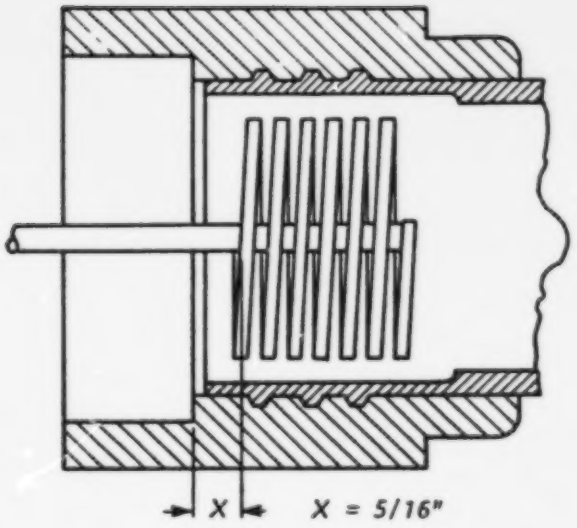


FIGURE 8
POSITION OF THE LOAD COIL

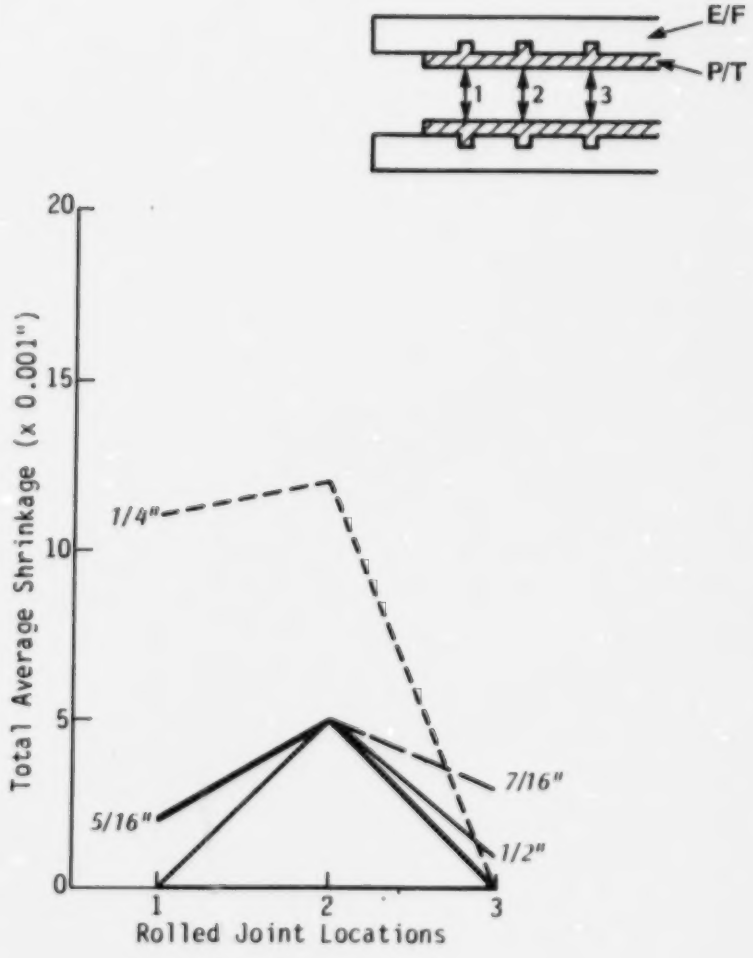


FIGURE 9

TOTAL AVERAGE SHRINKAGE VS ROLLED JOINT LOCATIONS AFTER THE FIRST HEATING CYCLE FOR VARIOUS COIL POSITIONS

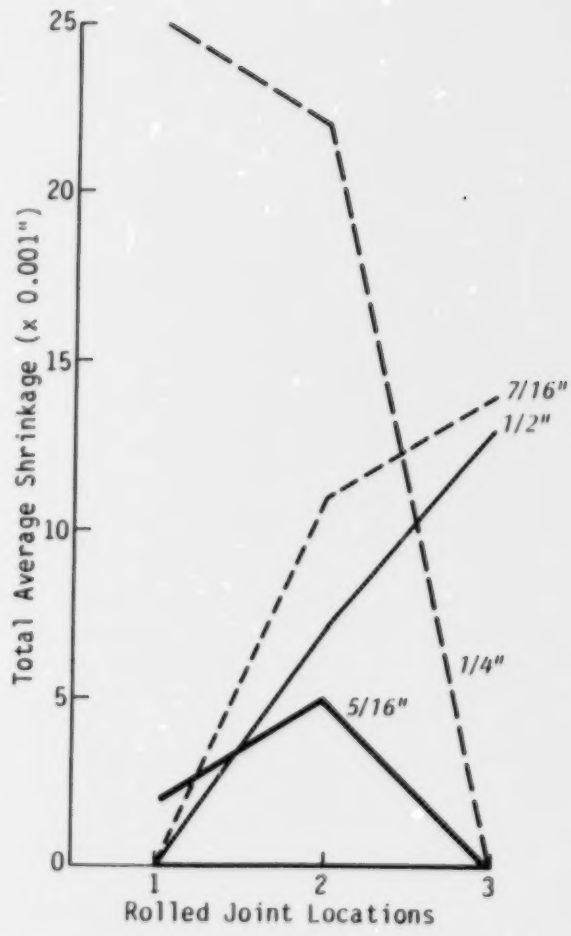


FIGURE 10

TOTAL AVERAGE SHRINKAGE VS ROLLED JOINT LOCATIONS AFTER THE SECOND HEATING CYCLE FOR VARIOUS COIL POSITIONS

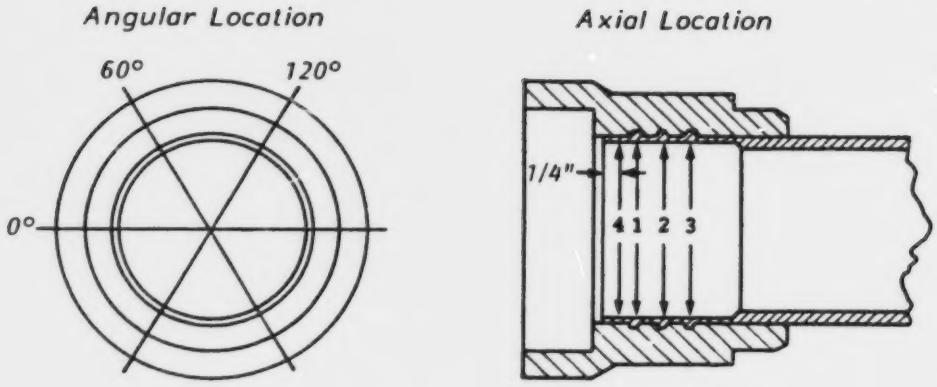


FIGURE 11
LOCATION FOR SHRINKAGE VERIFICATIONS

was to finalize the power level and duration of the heating and cooling cycles. This was necessary, since Zr-2 R/J samples consist of a different thickness P/T (5.23 mm as opposed to 4.16 mm for Zr-Nb 2.5% samples and a different P/T alloy (Zr-2 instead of Zr-Nb 2.5% by weight). The total number of heat cycles to be performed before attempting pulling was also established from the test results by taking measurements of the P/T shrinkage after each heat cycle. The locations for shrinkage verification are indicated in Figure 11. Statistical evaluation of these results, as outlined in Appendix I, showed that a total of nine heat cycles, of 30 s each, with cooling periods of 30 min between them was necessary. The power level corresponded to a plate dc voltage of 13.6 kV dc in these tests.

Average shrinkage measurements after nine heating and cooling cycles at various rolled joints location were obtained from data in Appendix I as follows.

Location	Shrinkage
1	0.156"
2	0.154"
3	0.140"
4	0.45"

8.5 Separation of Additional R/J's

At this stage, the main objective of the program was to separate an additional 14 Zr-2 R/J's in order to provide a sufficient number of samples (E/F hubs) for the R/J qualification program at CGE. In addition, it was decided to verify the procedure under a more stringent condition by leaving the R/J undisturbed during the heat cycles. It is believed that handling of R/J for measurement purposes may enhance the separation process due to slight jamming of a loose P/T in the E/F and continuous recentering of the induction heating coil in the R/J. Of course it would have been desirable to test the proposed procedure under fully simulated field conditions, but this was postponed for the subsequent phases of the program (Phase II of CRNL and Phase III at CGE) due to the very tight schedule.

All fourteen R/J's were separated on schedule/2/. The E/F surface in the rolled joint area appeared to be very clean and in good condition. However, some R/J's required more than the projected nine heat cycles to separate. Five out of eight initial R/J's required a contingency procedure due to undershrinkage. Problems with the Lepel equipment were suspected (aging of the oscillator tube). This problem was

TABLE I

SUMMARY OF P/T ID MEASUREMENTS AFTER APPLICATION OF LAST HEAT CYCLE AND PULLING FORCE APPLIED TO SEPARATE P/T-E/F-R/J

Ref 1	TOTAL NUMBER OF HC = 7				
	1	2	3	4	FORCE
0°	4.009	4.002	4.006	4.105	0 lb
60°	4.007	4.006	4.008	4.093	
120°	4.011	4.007	4.007	4.105	
Ref 2	TOTAL NUMBER OF HC = 8				
	1	2	3	4	
0°	4.039	3.980	4.000	4.128	0 lb
60°	4.077	4.020	4.000	4.117	
120°	4.048	4.009	4.047	4.122	
Ref 3	TOTAL NUMBER OF HC = 7				
	1	2	3	4	
0°	4.031	4.019	4.031	4.120	0 lb
60°	4.032	4.018	4.025	4.122	
120°	4.035	4.019	4.035	4.124	
Ref 4	TOTAL NUMBER OF HC = 11				
	1	2	3	4	
0°	4.071	4.012	4.030	4.107	4300 lb
60°	4.063	4.011	4.023	4.121	
120°	4.074	4.013	4.052	4.121	
Ref 6	TOTAL NUMBER OF HC = 7				
	1	2	3	4	
0°	4.010	3.997	4.015	4.117	0 lb
60°	4.030	4.020	4.022	4.118	
120°	4.020	3.999	4.024	4.119	
Ref 7	TOTAL NUMBER OF HC = 8				
	1	2	3	4	
0°	4.024	3.999	4.036	4.126	0 lb
60°	4.023	4.009	4.038	4.038	
120°	4.021	3.995	4.027	4.027	
Ref 8	TOTAL NUMBER OF HC = 8				
	1	2	3	4	
0°	3.996	4.002	4.051	4.121	0 lb
60°	3.986	4.000	4.024	4.122	
120°	4.003	4.009	4.028	4.133	
Ref 9	TOTAL NUMBER OF HC = 9				
	1	2	3	4	
0°	3.986	3.981	4.026	4.109	0 lb
60°	3.981	3.987	4.024	4.103	
120°	3.981	3.983	4.000	4.092	

Table 1 cont

Ref 10	TOTAL NUMBER OF HC = 12				
	1	2	3	4	FORCE
0° 60° 120°	4.000 3.994 3.998	3.990 3.988 3.989	4.012 4.019 4.020	4.115 4.108 4.112	0 lb
Ref 11	TOTAL NUMBER OF HC = 9				
	1	2	3	4	
0° 60° 120°	3.975 3.997 3.975	3.975 3.975 3.983	3.994 4.010 4.019	4.100 4.095 4.103	0 lb
Ref 12	TOTAL NUMBER OF HC = 9				
	1	2	3	4	
0° 60° 120°	4.023 4.012 4.01[illegible]	3.986 4.015 4.027	3.997 4.040 4.053	4.103 4.119 4.112	3200 lb
Ref 13	TOTAL NUMBER OF HC = 9				
	1	2	3	4	
0° 60° 120°	4.037 4.057 4.056	4.017 4.041 4.032	4.038 4.047 4.048	4.079 4.114 4.120	200 lb
Ref 14	TOTAL NUMBER OF HC = 12				
	1	2	3	4	
0° 60° 120°	4.041 4.052 4.051	4.028 4.049 4.003	4.050 4.058 4.098	4.103 4.112 4.114	2100 lb
Ref 15	TOTAL NUMBER OF HC = 10				
	1	2	3	4	
0° 60° 120°	4.025 4.024 4.047	4.015 4.015 4.044	4.045 4.045 4.055	4.104 4.118 4.114	1650 lb
Ref 16	TOTAL NUMBER OF HC = 11				
	1	2	3	4	
0° 60° 120°	4.054 4.067 4.067	4.024 4.030 4.017	4.038 4.028 4.052	4.114 4.120 4.094	0 lb
Ref 17	TOTAL NUMBER OF HC = 9				
	1	2	3	4	
0° 60° 120°	4.038 4.068 4.067	4.009 4.042 4.036	4.038 4.060 4.076	4.124 4.129 4.125	3300 lb
Ref 18	TOTAL NUMBER OF HC = 12				
	1	2	3	4	
0° 60° 120°	4.015 4.040 4.035	4.004 4.008 4.042	4.005 4.050 4.054	4.096 4.109 4.111	0 lb

Table 1 cont

Ref 19	TOTAL NUMBER OF HC = 7				
	1	2	3	4	FORCE
0° 60° 120°	4.026 4.036 4.075	4.022 4.009 4.021	4.036 4.026 4.035	4.089 4.091 4.104	300 lb
Ref 20	TOTAL NUMBER OF HC = 7				
	1	2	3	4	
0° 60° 120°	4.026 4.040 4.027	4.024 4.025 4.018	4.004 4.002 4.024	4.076 4.097 4.097	0 lb
CS 1	TOTAL NUMBER OF HC = 9				
	1	2	3	4	
0° 60° 120°	4.103 4.109 4.096	4.047 4.047 4.034	4.054 4.042 4.039	4.110 4.111 4.110	1650 lb
CS 2	TOTAL NUMBER OF HC = 10				
	1	2	3	4	
0° 60° 120°	4.036 4.045 4.030	3.986 3.975 3.997	4.005 4.008 4.047	4.113 4.009 4.098	0 lb
CS 3	TOTAL NUMBER OF HC = 9				
	1	2	3	4	
0° 60° 120°	4.026 4.023 4.036	4.020 4.032 4.007	4.007 4.024 4.032	4.111 4.113 4.113	2000 lb
CS 4	TOTAL NUMBER OF HC = 11				
	1	2	3	4	
0° 60° 120°	4.029 4.032 4.035	4.027 4.032 4.026	4.055 4.080 4.061	4.100 4.118 4.100	300 lb
CS 5	TOTAL NUMBER OF HC = 11				
	1	2	3	4	
0° 60° 120°	4.059 4.058 4.057	4.019 3.992 3.982	4.036 4.032 4.075	4.109 4.098 4.098	0 lb
CS 6	TOTAL NUMBER OF HC = 7				
	1	2	3	4	
0° 60° 120°	4.067 4.050 4.051	3.986 3.975 3.950	4.046 4.028 4.059	4.087 4.087 4.087	0 lb

compensated by increasing the dc voltage from 13.6 kV to 14.5 kV (corresponding to a computer power setting of 151) for the remaining six R/J specimens. Four out of six R/J's did not require the contingency procedure. The results of all 25 Zr-2 R/J specimens are summarized in Table 1.

9. CONCLUSIONS

Phase I of the LSFCR program (January 31, 1984 to June 2, 1984) was completed on schedule. The following results were accomplished during development of that phase:

- A procedure was developed for the application of the shock heating technique to the separation of Zr-2 P/T to E/F rolled joints. A total of 26 R/J's were separated using the established procedure. The E/F's came out clean and appeared free from damage under visual inspection. The separated E/F's and P/T's were sent to Canadian General Electric as requested by Pickering Engineering Department for refurbishing of the E/F Specimens and verifying that they could be reused for making new rolled joints.

- The shock heating process for separation of P/T-E/F rolled joint is reliable and yields results which are repeatable within the acceptable limits of statistical variation. The process parameters are controlled by computer and the demonstrated process repeatability assures that no adverse effects on E/F exist after shock heating.

- A prototype transmission line and coil assembly was built for integration into the system for field use.

- A technical specification/3/ was prepared for the procurement of the induction heating generator for field use.

Note that the fast induction heating process and system with practical modifications implemented in Phases II, III and IV have been successfully/4/used for separation of R/J in Units 1 and 2 at Pickering 'A' NGS. Results of the subsequent phases of the program will be provided in separate reports.

10. RECOMMENDATIONS

Further development work is recommended to optimize the fast induction heating technique for future rehabilitation of CANDU reactors.

Recommended by:

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Approved:

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H. Maureira
Engineer
Electromagnetic Studies Unit
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MC/MKN/HM:lg/11g

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1. Mario K.C. Ng, "Control and Monitoring System for Fast Induction Heating Equipment", Ontario Hydro Research Report No. 85-60-K, April 22, 1985.

2. M. Ćenanović, "Shock Heating - Pickering NGS 'A' LSFCRP Early Retube - Reuse of East End Fitting", memorandum to B.J. Murdoch, May 31, 1984, File 823.45(P).

3. M. Ćenanović, "Specification for Induction Heating Equipment", memorandum to J. Morcom, April 3, 1984, File 823.42.

4. K.H. Talbot, "Pickering NGS, Unit 1 and 2 Progress Report No 73, Period Covering (September 23 - September 30, 1985)", September 30, 1985.

APPENDIX I

STATISTICAL ANALYSIS OF P/T SHRINKAGE MEASUREMENTS

Figure a) Statistical analysis of P/T initial ID measurements

Figure b) Statistical analysis of P/T shrinkage measurements after the 1st cycle

Figure c) Statistical analysis of P/T shrinkage measurements after the 2nd cycle

Figure d) Statistical analysis of P/T shrinkage measurements after the 3rd cycle

Figure e) Statistical analysis of P/T shrinkage measurements after the 4th cycle

Figure f) Statistical analysis of P/T shrinkage measurements after the 5th cycle

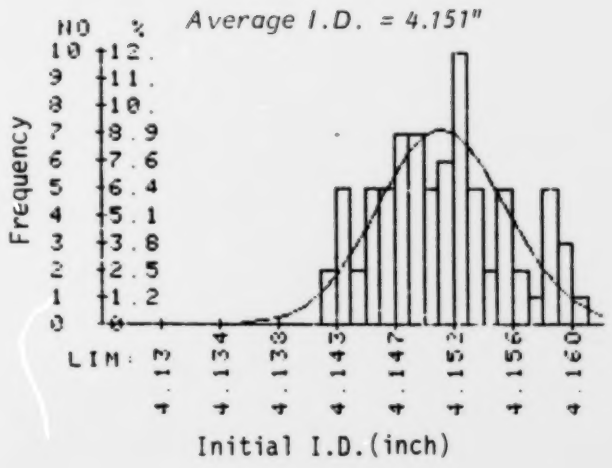
Figure g) Statistical analysis of P/T shrinkage measurements after the 6th cycle

Figure h) Statistical analysis of P/T shrinkage measurements after the 7th cycle

Figure i) Statistical analysis of P/T shrinkage measurements after the 8th cycle

Figure j) Statistical analysis of P/T shrinkage measurements after the 9th cycle

Figure k) Summary of statistic results obtained from Figures a-j



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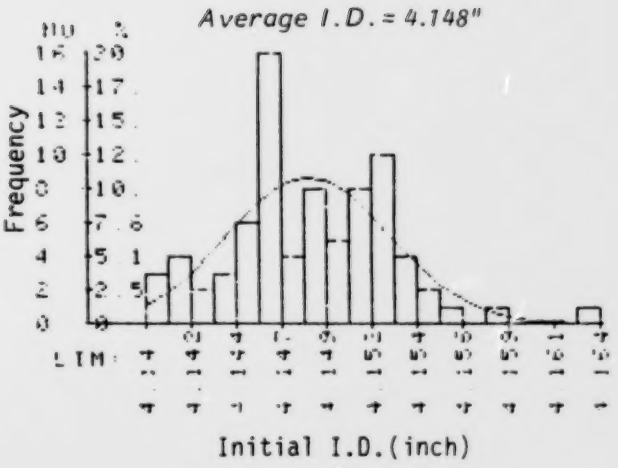

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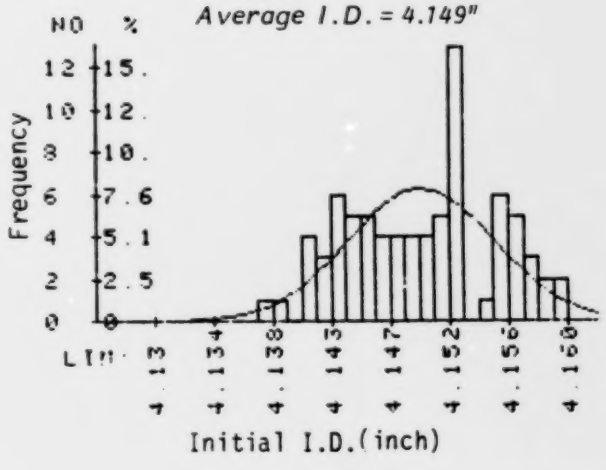

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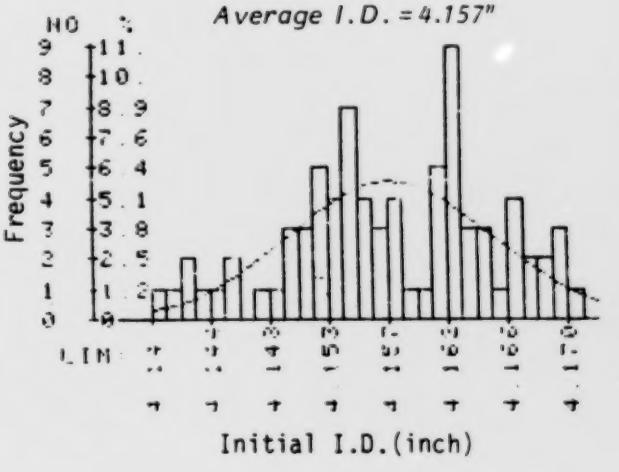
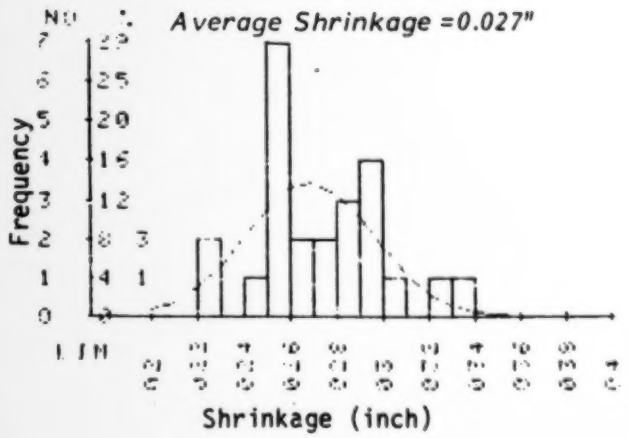


Location 4

FIGURE a

STATISTICAL ANALYSIS OF P/T INITIAL I.D. MEASUREMENTS



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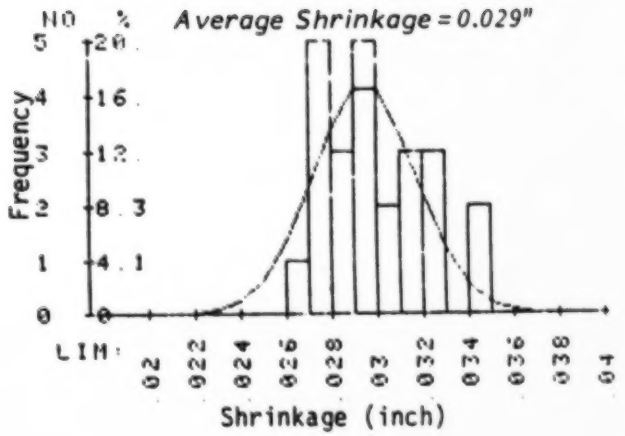

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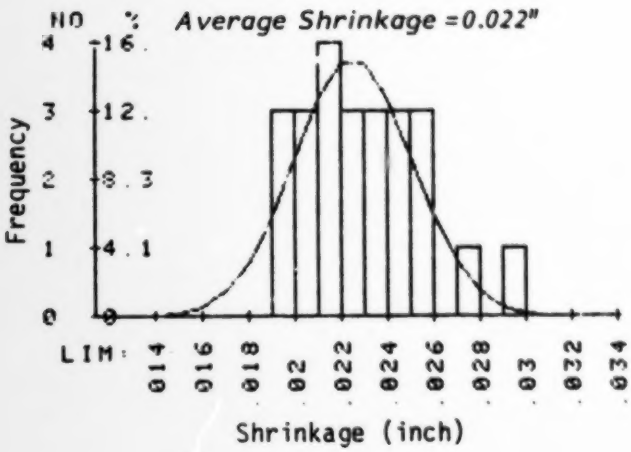

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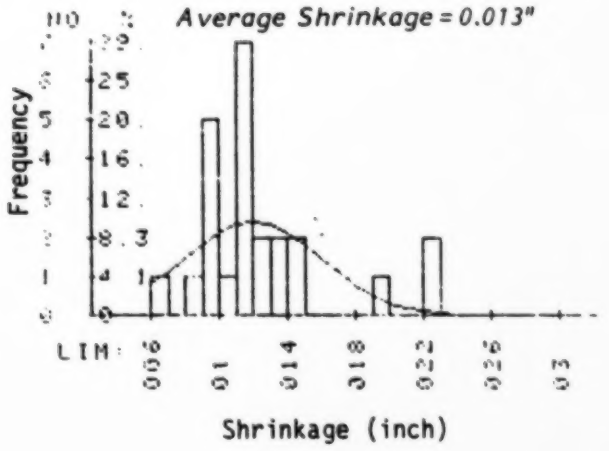
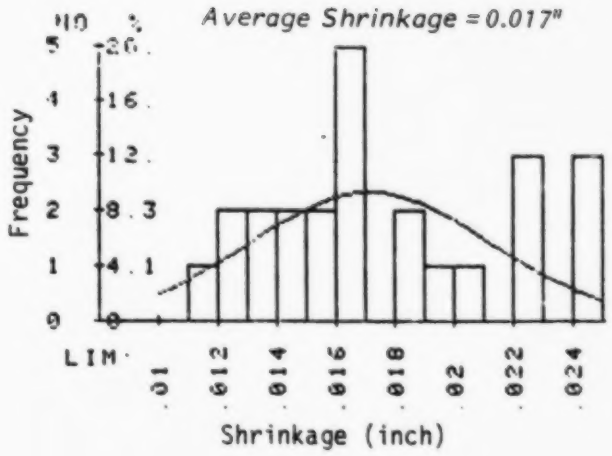


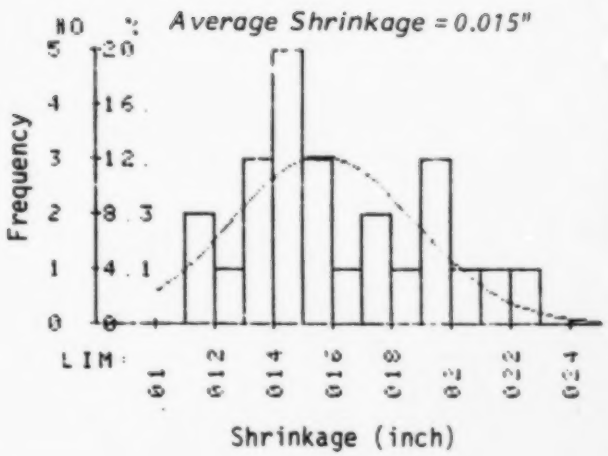
Location 4

FIGURE b

STATISTICAL ANALYSIS OF P/T
SHRINKAGE MEASUREMENTS AFTER 1st CYCLE



Location 1



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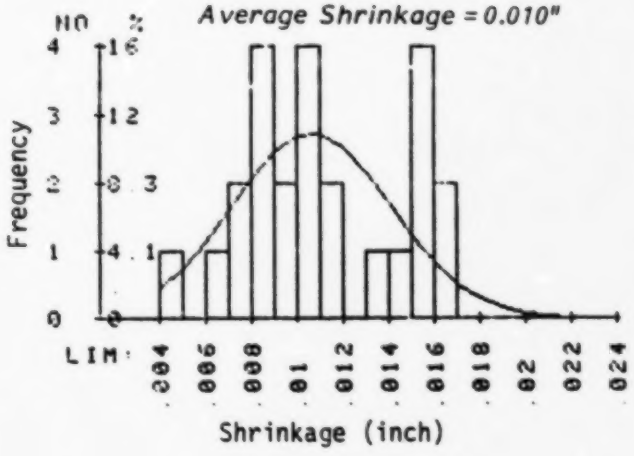

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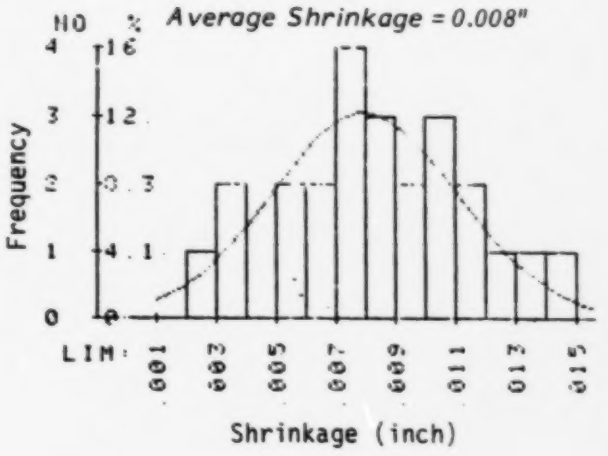
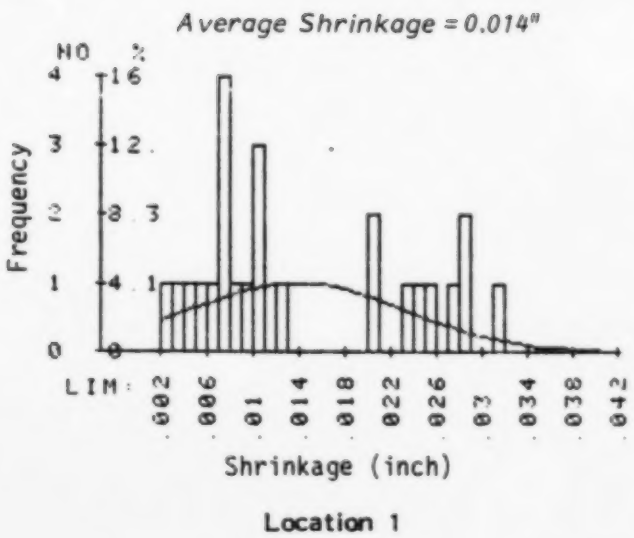


Location 4

FIGURE c

STATISTICAL ANALYSIS OF P/T SHRINKAGE MEASUREMENTS AFTER 2nd CYCLE



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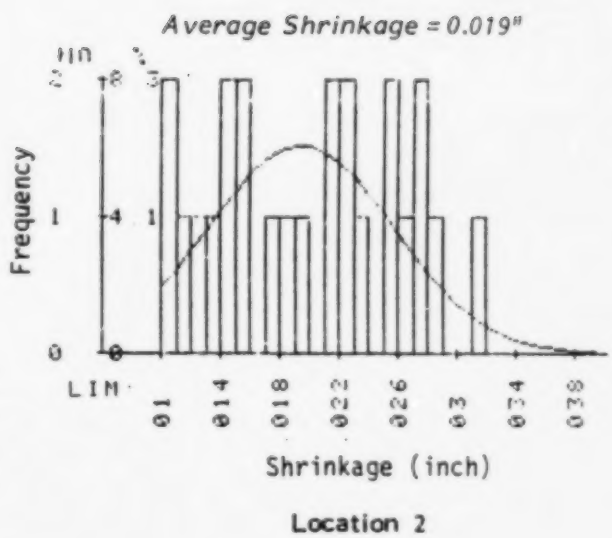

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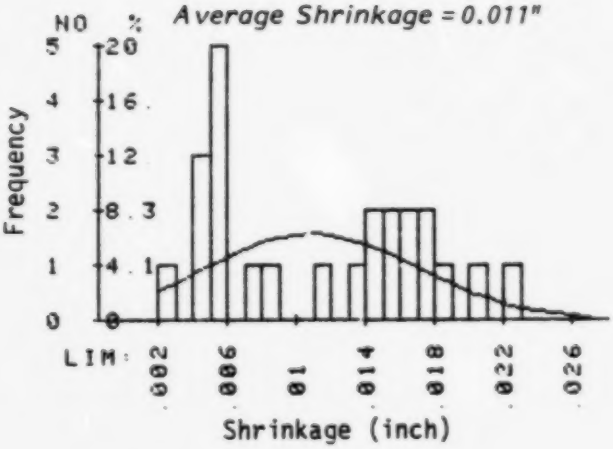

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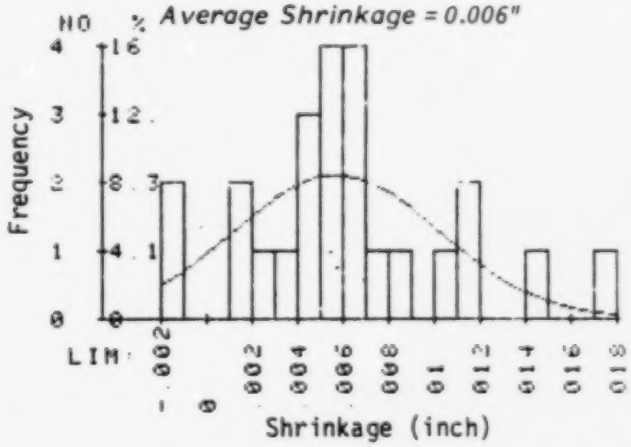
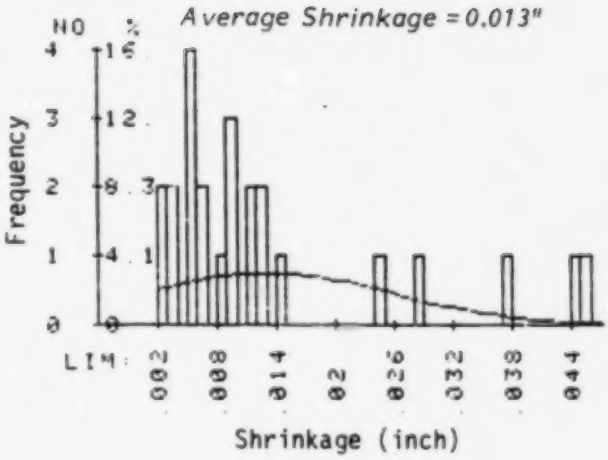


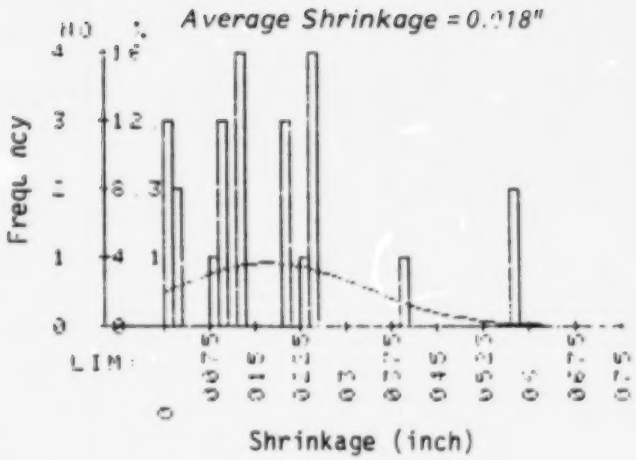
Location 4

FIGURE d

STATISTICAL ANALYSIS OF P/T SHRINKAGE MEASUREMENTS AFTER 3rd CYCLE



Location 1



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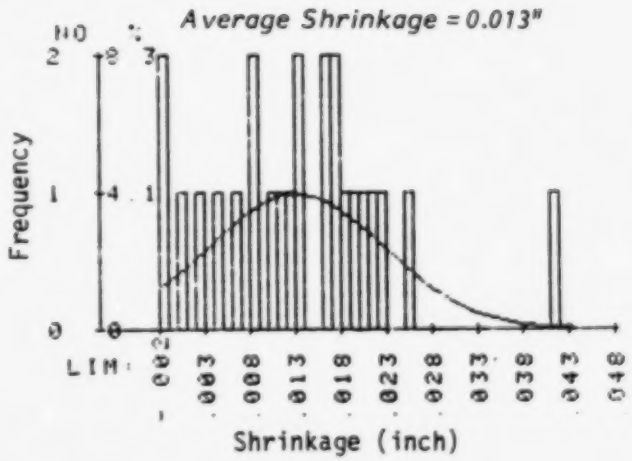

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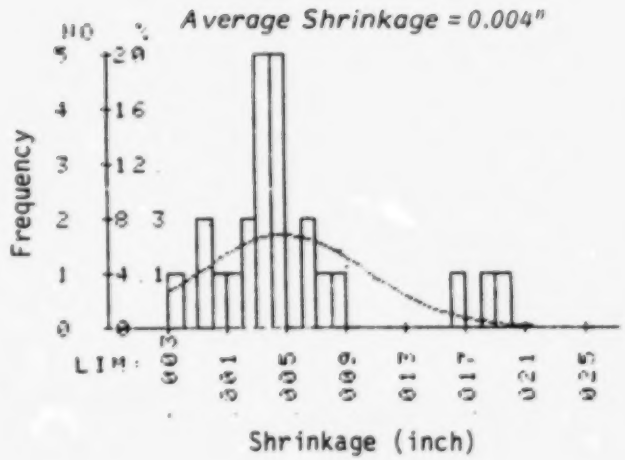
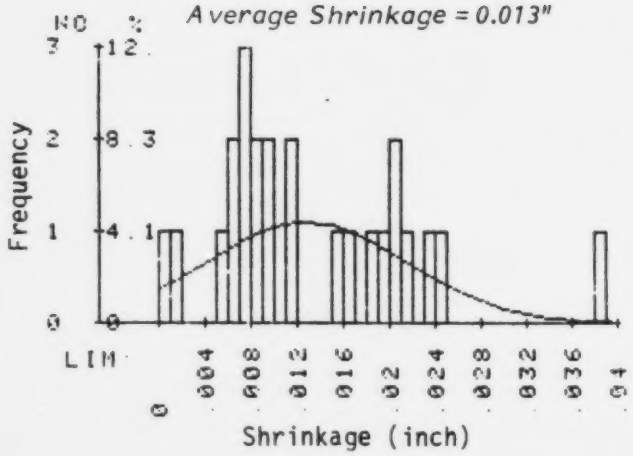


Location 4

FIGURE e

STATISTICAL ANALYSIS OF P/T
SHRINKAGE MEASUREMENTS AFTER 4th CYCLE



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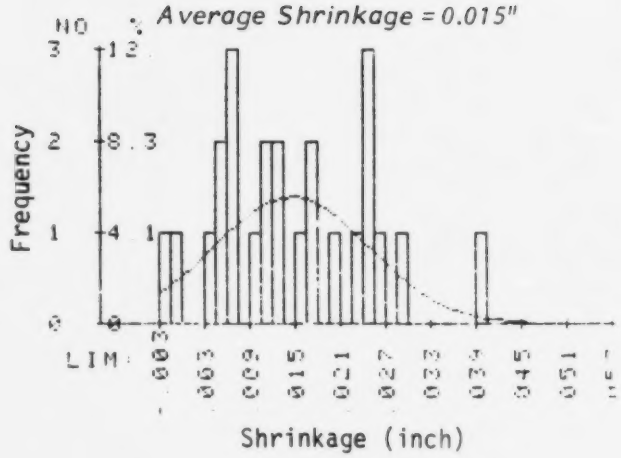

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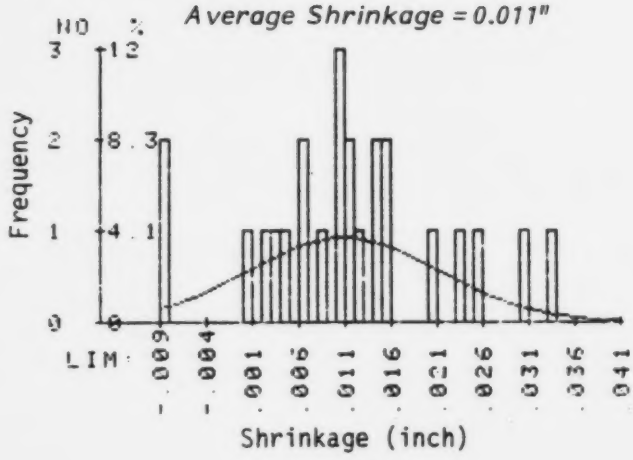
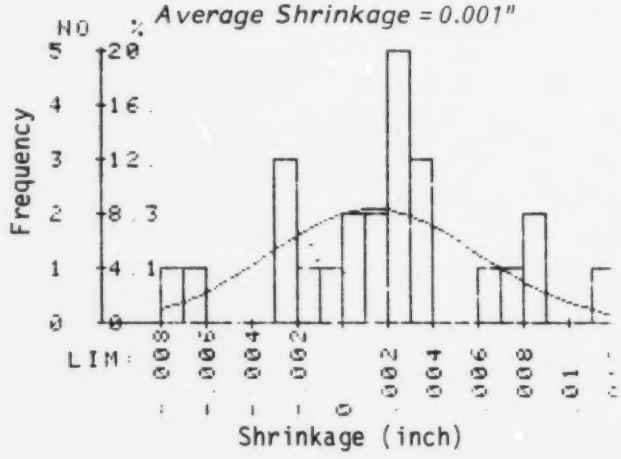


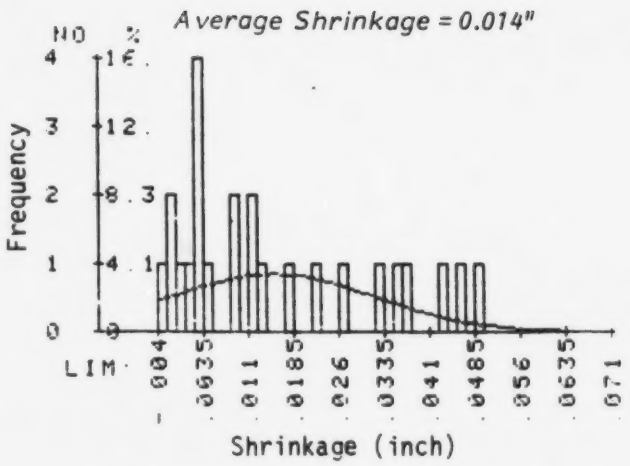
Location 3



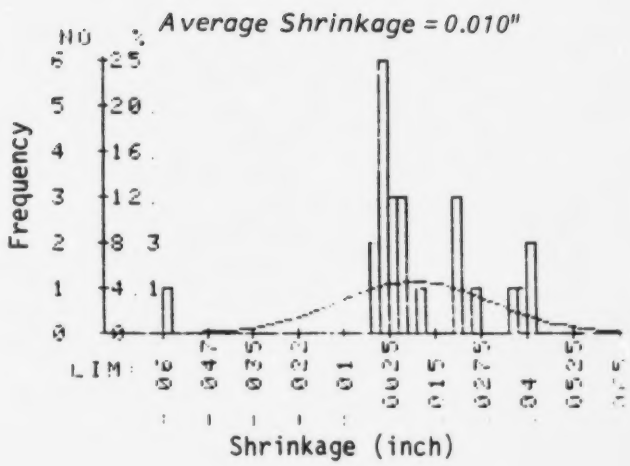
Location 4

FIGURE f

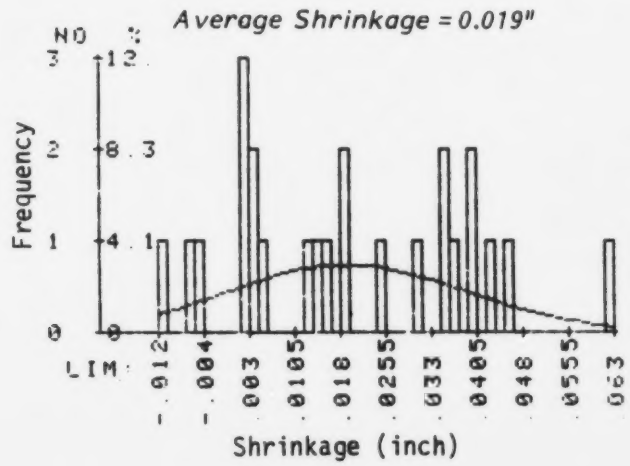
STATISTICAL ANALYSIS OF P/T SHRINKAGE MEASUREMENTS AFTER 5th CYCLE



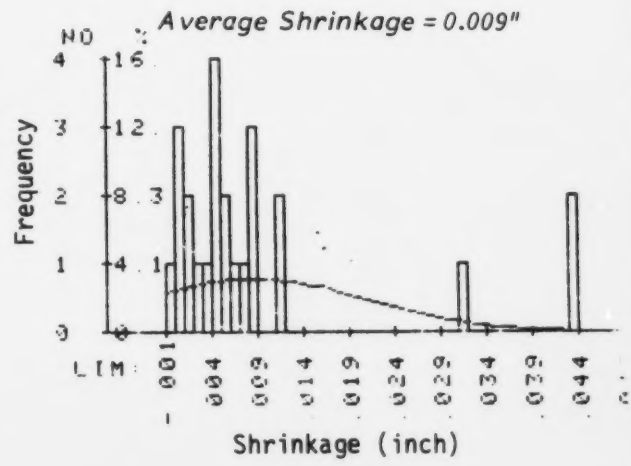
Location 1



Location 2



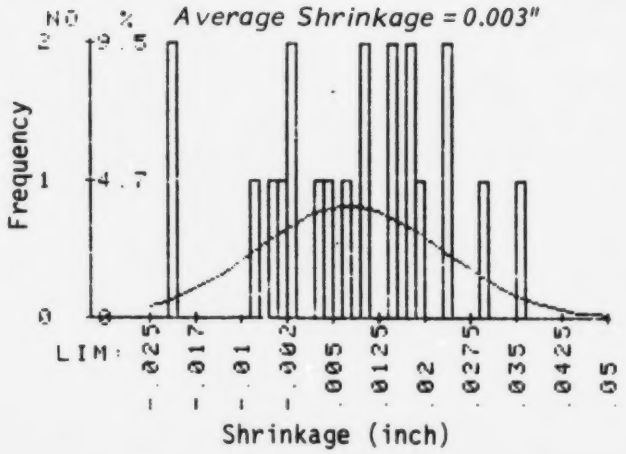
Location 3



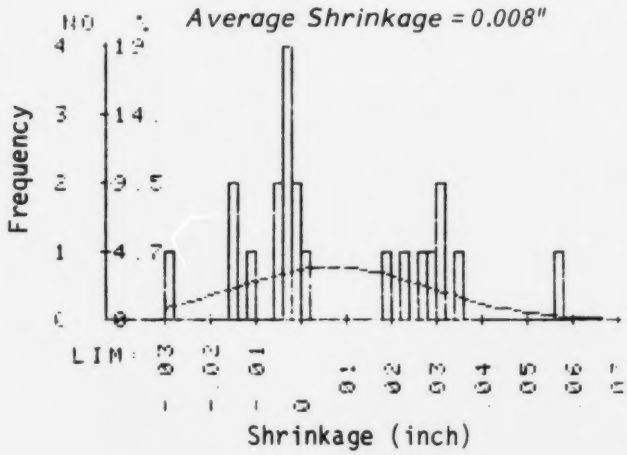
Location 4

FIGURE 9

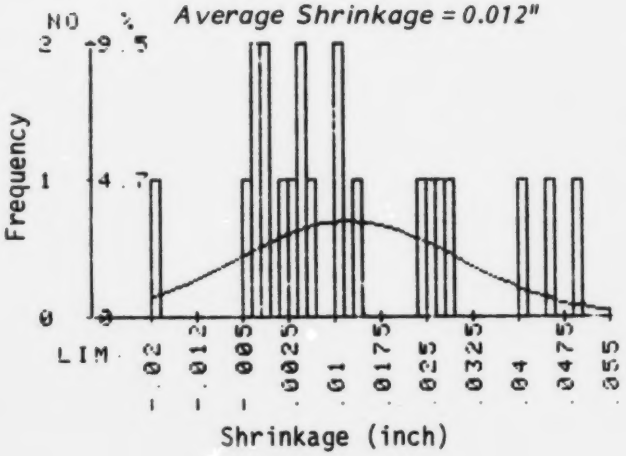
STATISTICAL ANALYSIS OF P/T SHRINKAGE MEASUREMENTS AFTER 6th CYCLE



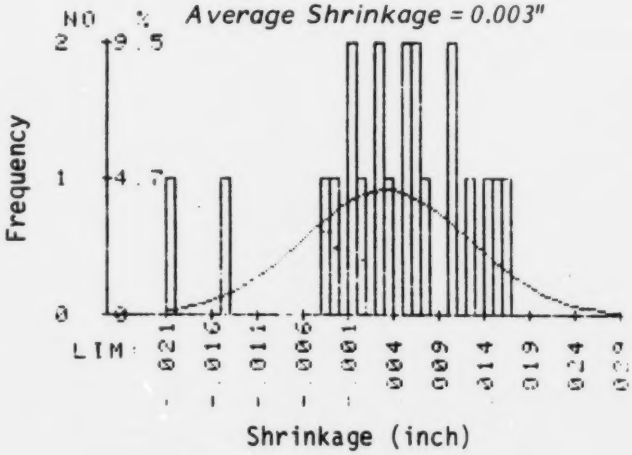
Location 1



Location 2



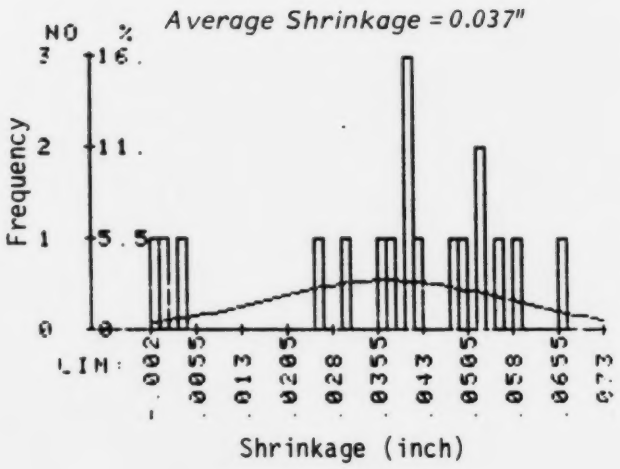
Location 3



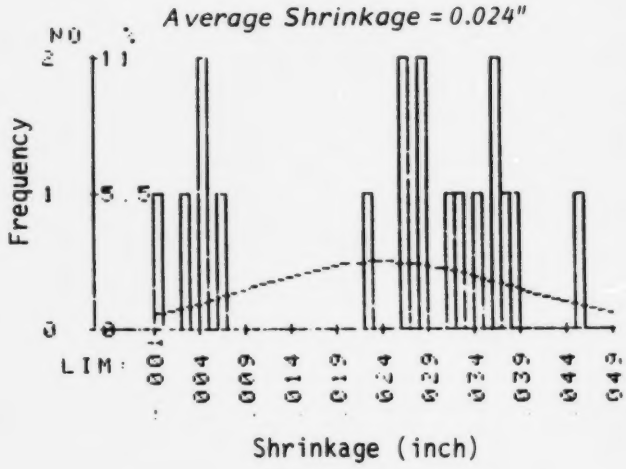
Location 4

FIGURE h

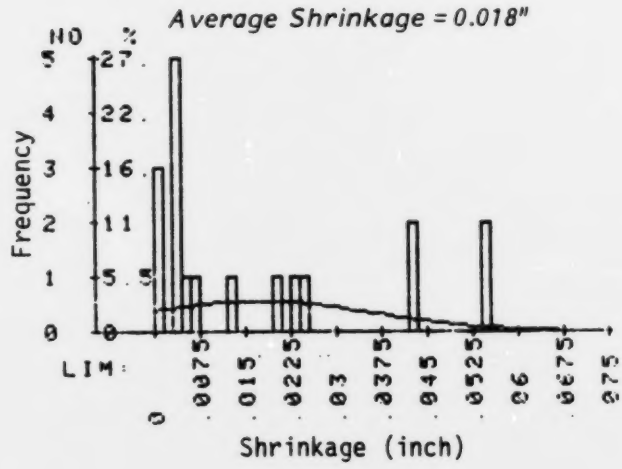
STATISTICAL ANALYSIS OF P/T SHRINKAGE MEASUREMENTS AFTER 7th CYCLE



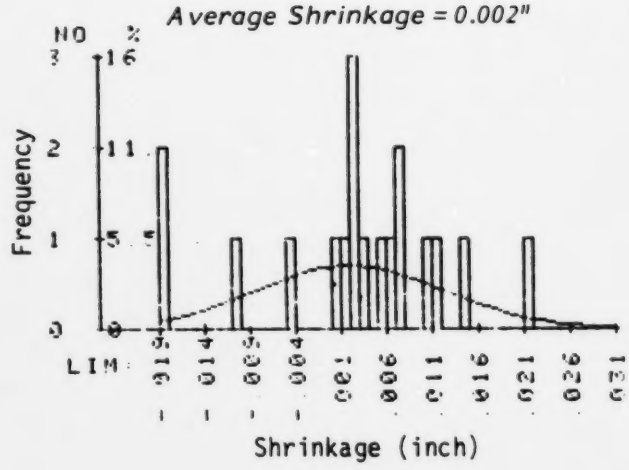
Location 1



Location 2



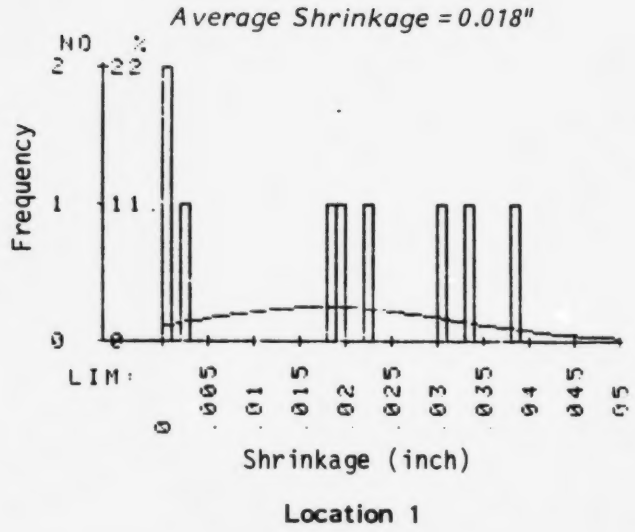
Location 3



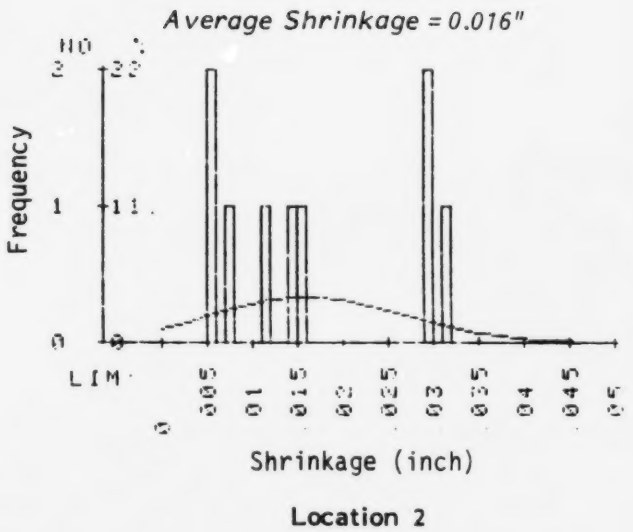
Location 4

FIGURE i

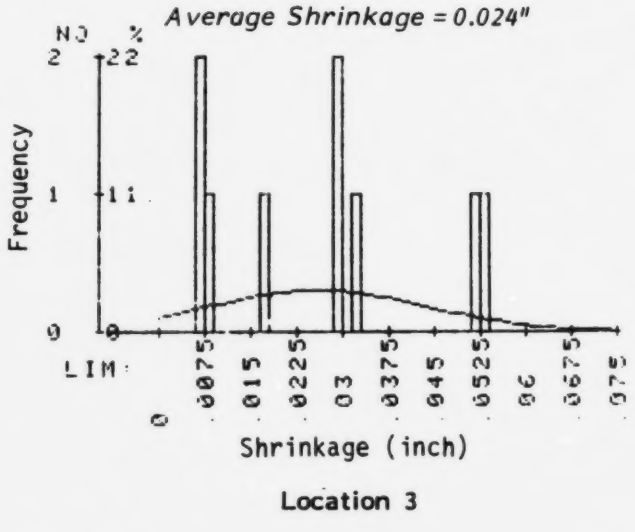
STATISTICAL ANALYSIS OF P/T SHRINKAGE MEASUREMENTS AFTER 8th CYCLE



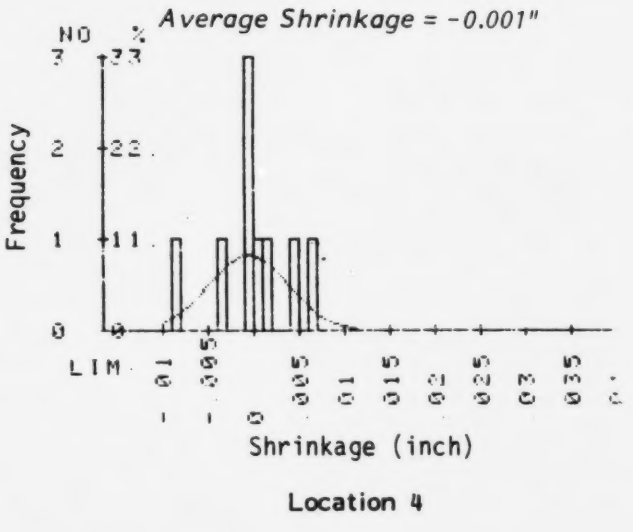
Location 1



Location 2



Location 3



Location 4

FIGURE j

STATISTICAL ANALYSIS OF P/T SHRINKAGE MEASUREMENTS AFTER 9th CYCLE

	Statistical Average I.D. Measurement (inches)				Statistical Average P/T Shrinkage (x 0.001")			
	Location Number				Location Number			
	4	1	2	3	4	1	2	3
Initial	4.157	4.151	4.148	4.149				
1	4.144	4.124	4.119	4.127	13	27	29	22
2	4.136	4.107	4.104	4.117	8	17	15	10
3	4.130	4.093	4.085	4.106	6	14	19	11
4	4.126	4.080	4.067	4.093	4	13	18	13
5	4.125	4.067	4.052	4.082	1	13	15	11
6	4.116	4.053	4.042	4.063	9	14	10	19
7	4.113	4.050	4.034	4.051	3	3	8	12
8	4.111	4.013	4.010	4.033	2	37	24	18
9	4.112	3.995	3.994	4.009	-1	18	16	24
Total P/T Shrinkage After 9 Heating Cycles					45	156	154	140

FIGURE k

SUMMARY OF STATISTICAL RESULTS
OBTAINED FROM FIGURES a-j